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Subaqueous Railroad Tunnels

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SUBAQUEOUS RAILROAD TUNNELS

BY

CHARLES SUMNER STEWART

THESIS

FOR THE

DEGREE OF BACHELOR OF SCIENCE

IN

CIVIL ENGINEERING

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CHARLES SUMNER STEWART

ENTITLED SUBAQUEOUS RAILROAD TUNNELS

IS APPROVED BY ME AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

DEGREE OF Bachelor of Science in Civil Engineering

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INTRODUCTION.

The subject of sub-aqueous tunneling covers only a small part of the whole subject of tunnels, but it deals with the most difficult problems in tunnel engineering. Other tunnels may be longer, but it is seldom that the difficulties met with in land tunnels are as hard to overcome as those encountered in sub-aqueous tunnels. The subject of sub-aqueous railroad tunnels while it does not cover the whole ground of tunnels constructed under water is no doubt the most important branch of that subject. Other purposes for which such tunnels have been constructed are; for carrying canals, sewers, gas pipes, water mains, and highways. This thesis will be confined to sub-aqueous railroad tunnels, except in cases where it is considered advisable to describe other tunnels in order to show some special feature of construction or a stage in the development of sub-aqueous tunneling methods. The thesis is divided into three parts.

The first part of the thesis is a brief history of sub-aqueous tunneling and is intended to show the stages in the development of methods of construction up to the present time, and the increase, in recent years, of the amount of such work done.

The second part deals with the economics of sub-aqueous tunnels. The conditions rendering such tunnels necessary or desirable are described. A comparison is made between sub-aqueous tunnels and other means of transportation, that serve the same purpose, on the grounds of, first cost, maintenance, results, and

durability.

The third and major part of this thesis is on construction. Here is described in as complete detail as possible the following items; general requirements for sub-aqueous tunnels, the engineering work, methods of construction, materials encountered, foundations, linings, waterproofing, and drainage. These will be treated usually by describing a typical tunnel and noting differences that are found in others.

I am indebted to Mr. A. C. Everham, Assistant Engineer of the Detroit River Tunnel Company, for the photographs showing the methods of construction of that tunnel, and to Mr. Noble, Chief Engineer of the Pennsylvania Tunnel and Terminal Railroad Company, for the photographs of that work.

CHAPTER I.

HISTORY OF SUB-AQUEOUS TUNNELING.

Since sub-aqueous tunneling began before railroads came into use it will be necessary to describe some early tunnels that were not railroad tunnels. The earliest use to which tunneling in soft ground was put was to carry canals. Though this cannot strictly be called sub-aqueous tunneling the methods used and problems dealt with were the same as met in that kind of tunnel. The earliest tunnel proper on an English canal was the Hardcastle Tunnel No. 1, situated on the Grand Trunk Canal. This tunnel which was built by James Brindley was begun in 1766 and opened in 1777. Several other canal tunnels were built in the next few years.

The first tunnel under the Thames was proposed by Dodd in 1798. Work was begun in 1807 but the eruption of water caused several delays and it was not opened to traffic till 1843. The tunnel is 38 ft. wide and 22 1/2 ft. high. The shield used was in twelve independent sections, weighed 120 tons, and accommodated 36 workmen at a time. The cost of the tunnel was $6000 per linear yard. It was used for vehicles and foot passengers only.

The second tunnel under the Thames was constructed in 1868-69. Its length was 1320 ft. and its diameter 8 ft. It was driven by means of a shield weighing 2 1/2 tons, accommodating 3 men. The water encountered was very slight. The shield advanced at the rate of 9 ft. in 24 hours. The motive power was six screw jacks

operated by hand. By means of these a pressure of 60 tons could be brought to bear on the shield.

The first sub-aqueous railroad tunnel attempted in this country was the Detroit river tunnel. This was begun in 1872 and after encountering many difficulties, the principal one being large quantities of water under high pressure, the work was abandoned in 1873. It was thought advisable to run an 8 ft. drainage tunnel entirely across the river in order to give the contractor an idea of what sort of material he would have to work in, also to drain the main tunnel and form a reservoir for water in case the pumps became disabled. This was run for 1200 ft. out from shore and large amounts of quicksand and water pockets were met with. The main tunnel was then begun ten ft. higher than the old drift and no difficulty was had until a point 20 ft. beyond the end of the old drift was reached. A large irruption of water occurred here. The two drifts were worked alternately until the contractors became discouraged at the slow progress and high cost and abandoned the work. It is interesting to note that the site of the first attempt at sub-aqueous railroad tunneling in America is now seeing the completion of a tunnel by a method that will revolutionize sub-aqueous tunnel construction.

The Hudson Tunnel Railroad Company was organized with a capital of $10,000,000. The tunnel was begun in 1879. The Hudson river is 5500 ft. wide where the tunnel crosses. This was the first tunnel in which compressed air was tried. The tunnel was delayed considerably on account of leaks and blowouts. The tunnel was finally completed about twenty years after it was begun.

The completion of the work was by English Engineers with English capital.

In 1873 a tunnel was begun under the Severn river and in 1881 under the Mersay. Both were opened in 1886. They were driven by a drift method, lined with brick and both single tube double track railroad tunnels.

Recently a great many tunnels have been built. One or more has been in process of construction all the time. There are now 16 tubes under the North river and East river about New York City. Three tunnels pass under the Thames at London. Other important tunnels recently constructed are The Spree at Berlin in 1899, St. Clair, 1891, Detroit tunnel, 1909, the Seine, East Boston and the Harlem river.

It is probable that tunnel construction in the next few years will be a large item in railroad work. The latest methods of construction with the advantages of tunnels over bridges will lead to the construction of tunnels across such rivers as the St. Lawrence, Mississippi, Ohio and others.

CHAPTER II.

ECONOMICS OF SUB-AQUEOUS TUNNELS.

I. Conditions best suited to sub-aqueous tunnels. When it becomes necessary or desirable for a railroad company to carry its traffic across a body or stream of water without the inconvenience of transferring it from car to boat and then from boat to car, the first method used is the car ferry. This is the most economical when the traffic is light. As the amoung of traffic increases the cost of this sytem increases in nearly the same ratio. Also with an increase of traffic comes the need of greater speed, especially in the case of the handling of passengers and perishable freight.

The choice then is between a tunnel and a bridge. The conditions best suited to sub-aqueous tunnels are: a soil consisting of stiff clay or soft rock, a broad thinly settled plain on each side of the river, and at an elevation only slightly above that of the river. The variation on level of the river should not be great enough to overflow this plain. The depth of the river should not be greater than is necessary to allow boats to pass at all seasons of the year. The railroad traffic should be great enough that the tunnel is in use practically all the time. These are the ideal conditions for the location of a sub-aqueous tunnel but in practice the last one is what usually determines the building of the tunnel. The location is usually fixed within certain limits by other conditions such as the location of trunk lines and large cities.

2. Conditions necessitating sub-aqueous tunnels. When the conditions become such that a car ferry is no longer economical the choice lies between a tunnel and a bridge. The conditions must be studied carefully from the point of view of capitalized cost and the most economical structure decided upon. If the water to be crossed is an arm of the sea and there is likely to be damage to the piers of a bridge from heavy seas that structure is not considered allowable. It is then necessary to construct a tunnel. On the other hand the local conditions may be more favorable for the bridge than for the tunnel but the interests of navigation may be injured by obstructing the stream by piers. These interests may be strong enough to prevent the government from granting permission to construct a bridge. This was the case at Detroit where the Cnadian government refused to give its consent for a bridge as long as a tunnel was considered possible.

3. Comparison of tunnels with other means of transportation. Ferries; First cost. In this comparison it will be necessary to take systems of the same capacity. A double track tunnel two miles long will deliver a train from one portal to the other in 8 minutes at the outside. Since one train is not allowed to start until the preceding one has passed the station on the other side 10 minutes may be taken as a reasonable time for each train. This gives a capacity of 144 trains per day for each tube or 288 trains for both tubes. Taking an average of 25 cars per train gives 7200 cars per 24 hrs. as the capacity of the tunnel. The time required by a car ferry to load its train go across and unload is about 40 minutes under the most favorable conditions. The

average capacity of a ferry boat is about 15 cars distributed over three tracks. With the supposition that the ferry is busy the entire 24 hours, one boat will carry 540 cars in 24 hours or 13 boats will carry as much traffic as one double track tunnel. The equipment of the car ferry consists of approach tracks, adjustable slips and switching engines in addition to boats. If there is a great variation in the level of the water the slips become expensive. Even in the case of the Detroit river where the difference in level is not over a foot the slips occupy valuable property on the river front.

The tunnel at Detroit is estimated to cost $10,000,000 including all appurtenances. The principal items of cost in this are, the tunnel proper, the approach tracks, and receiving and storing yards, the power plant, and the equipment. The electric zone at Detroit is three miles long and since the special electric locomotives only work in these limits about 4 or 5 would be required to handle the traffic without causing delay. The first cost of a ferry system is without doubt much less than that of a tunnel.

Maintenance: Boats being subjected to storms, ice, danger from wrecks, and rapid deterioriation in value the maintenance from that source is relatively great. The cost of running a movable plant for furnishing power is always greater than that of a stationary plant, for the reason that the movable plant is in smaller units and more difficult to furnish fuel to. The furnaces in the boats must be fed by hand and the coal supplied in relatively small quantities and loaded on the boat at short

intervals. During this time when the boat is being coaled it is out of use. More men are needed to run the ferry system than the tunnel system. The number of boats required is about 2 1/2 times the number of locomotives. More than two men to each locomotive are never required and usually only one is necessary while at least six are needed on each boat. The car ferries often belong to several companies which may use the tunnel together when it is completed. The cost of such a system is increased in that one set of officials could do the work of all if the ferries were combined. Since this is done in the management of the tunnel and each railroad company pays the tunnel company or the railroad company owning the tunnel a specified amount for each car transferred the expense is less to all.

Results: A tunnel will save about 30 minutes in passenger and 2 to 3 hours in freight traffic in summer when conditions are at the best. This means a great deal in revenue from through passenger and freight traffic and especially in perishable freight. In winter when the river is full of ice, there have been times at Detroit when a boat and consequently a train was delayed 24 hours. With the tunnel there will be practically no difference in time of transit in summer and winter. This condition will draw much traffic through Detroit where before it was sent over other routes to secure greater certainty of transportation.

With the use of electric locomotives and the modern methods of ventilation and the ruling that no train is to enter a tube until the preceding one has passed the station on the other end the tunnel may be considered safer than the ferry from the stand

point of accidents to persons.

Durability: The tunnel proper is a permanent structure, the only parts of the system that will need renewing are the power plant buildings, machinery, and locomotives. The entire system of car ferries will require renewal after a time. The life of boats due to rough usage and new improvements being comparatively short, much shorter than the life of a building and of stationary machinery. It is not uncommon for a ferry boat to sink with its load entailing a heavy loss to the company while a similar loss on the tunnel system could hardly occur.

High level bridge: The tunnel possesses the following advantages over the high bridge. (1) Economy of first cost, (2) Great economy in cost of maintenance, (3) The tunnel requires the purchase of less land for approaches, (4) A tunnel can be extended across a city if necessary in order to avoid purchasing valuable property or interfering with business interests, (5) The gradients on a tunnel to the terminal points are descending in the case of a tunnel and ascending in the case of a bridge. Trains can be started and stopped more easily when entering and leaving a tunnel than a bridge.

Mr. Wm. Barclay Parsons, Chief Engineer of the New York Rapid Transit Commission says in regard to the proposed bridge or tunnel across the East river. " The two bridges contemplated between Manhattan and Brooklyn are estimated to cost $28,000,000, exclusive of interest during construction. Double track railroad tunnels on the same location would cost $8,000,000, or by extending the Blackwell's Island location from Second Ave. to Third or Fourth Ave. where the traffic facilities are much better

the cost of a tunnel would be $4,000,000, as against $12,500,000 for a bridge." From Canal St. to Elm St. the tunnel would cost $6,000,000, against $16,000,000 for a bridge. For $28,000,000, eight double track tunnels could be built across the river or 6 or 7 across both river and city.

There are many sources of expense in the maintenance of a bridge that do not occur in the case of a tunnel and few in the tunnel that do not occur on the bridge. A bridge must be painted and the members must be inspected frequently to avoid failure from weakening by winds, vibrations, etc. Piers must be protected from damage by boats and ice.

The roof of a tunnel must be at 35 ft. below low water, this places the rail base at 55 ft. approximately. A high bridge must be about 100 ft. above high water. This makes the gradient for the tunnel much less in getting to the surface than the gradient for the bridge approaches. The property above the tunnel can be occupied without inconvenience or loss while that beneath a bridge cannot so well be occupied.

In general it can be said that in most cases the tunnel has the advantage over both the ferry and high bridge from the standpoint of both the railroad company and the river transportation interests. The presence of ferry boats crossing the line of traffic of through boats and of ships occupying property that would be valuable for docks hinders shipping. The presence of piers in a stream also interferes with shipping and in some cases may cause the wreck of a boat and damage to the bridge.

It is unnecessary to compare the efficiency of a tunnel and

a draw bridge. When the railroad traffic becomes heavy enough to make the consideration of a tunnel necessary, it is too heavy to carry over a draw bridge. The conflict between water and railroad traffic is one thing that makes the consideration of a tunnel necessary. When the shipping interests are great enough for this the single or even double channel offered by the draw would not be sufficient for it. In other words, the river interests and railroad interests both require uninterrupted routes and the draw bridge furnishes neither. In the case of a draw bridge which would be low there would be more piers and consequently more danger of damage to the piers, bridge, and boats.

CHAPTER III.

CONSTRUCTION.

1. Ceneral requirements: Clearance for vessels. The minimum depth of a sub-aqueous tunnel is limited by the requirements for navigation. The highest point in the tunnel must be low enough to allow vessels a clear channel during low water or low tide if the water is navigable at this time. This minimum depth is set by the war department. It is only in the case of tunnels constructed from above that this regulation is likely to govern and not then if the channel is deep; for the tubes must be near enough to the river bed to be covered with a blanket of earth after completion. In the case of tunnels constructed by the shield method it is considered advisable to have a blanket of earth of from 10 to 15 ft. over the tunnel so it is improbable that the depth would ever be governed by this requirement of navigation. The proposed swedish method of supporting tubes on piers near the river bed would be regulated by this limitation.

Freedom from damage: The roof of the tunnel must be so located and protected that it will not be damaged by scouring of the river bed by the current, or by tides and will not be injured by wrecked boats settling upon it. If the roof is left exposed and to any height above the river bed there is danger from this source. To overcome this the tunnel tubes are covered with a blanket of clay which distributes the weight over a larger area. The clay is covered with rip rap to prevent scouring of the bed by currents. This is the principal objection to the proposed swedish tube tunnel and is no doubt the one reason that prevented

its being tried.

Easy Gradient: When sub-aqueous tunnels are driven by the shield method it is considered advisable to leave a considerable depth of earth between the shield and the river bed for safety during construction. This necessitates either steep gradients or long approaches. The first adds greatly to the operating expenses, the latter to the first cost of the tunnel. The condition to strive for is to have the roof of the tunnel at the minimum depth below the water level and still not interfere with river traffic. The maximum grade allowed is usually two per cent and under these conditions this can be secured without making the approaches extremely long. Another condition affecting the gradient is the condition of the adjoining country. If the tunnel opens in a thickly populated city where property is valuable it will be economical to make the approach as short as possible and therefore the gradient steep. Another condition not very likely to occur is to have the banks of the river on both sides high and near the waters' edge. This would make it necessary to bring the tunnel to the surface as soon as possible. A high bridge would probably be constructed under these conditions. If the tunnel is to open in a broad plain which is thinly populated, the first cost will not be unduly increased by making the approach long. This condition existed at both ends of the St. Clair tunnel and the maximum gradient was fixed at two per cent. Such favorable conditions also exist at the Canadian end of the Detroit River tunnel where the maximum gradient is 1.5 per cent, but the Detroit end of the same tunnel opens in the City and the gradient here

is two per cent. In order to show the relation between the practicability of securing flat grades as over against steep grades at a lower first cost and added annual expenditure we will examine these conditions from the standpoint of capitalized cost. In the following equation C is the capitalized cost, F the first cost, O the operating expenses, the rate of interest and n the life of the structure in years. C F . Since the life of a tunnel may be taken as a great many years the last term which is the depreciation may be neglected . In the equation C F it is seen that when the capitalized cost is constant the first cost may be increased by in order to decrease the operating expenses by one and still be economical. Thus if .05 F may be increased $20 in order to reduce the annual operating expenses by $1. This is a problem that faces every engineer on railway location and the expert judgment of an engineer on this point will be the means of saving thousands of dollars to the railroad company which he represents.

2. Engineering work: Preliminary work. Preliminary survey: The first thing to do after a tunnel has been decided on is to examine all possible sites and decide which one or two are apparently best located. If more than one is chosen a few test borings are taken to determine the character of the material to be penetrated. If one of these shows more favorable prospects than the other it is chosen. It is more often the case that the tunnel must be built to connect two existing tracks and almost no room is left for choice of location. When an approximate line is decided upon a number of borings are taken over the center line of the land portion of the tunnel and about 50 ft. each side of the

center line of the sub-aqueous portion. This distance is chosen in order that if the exact location of the tunnel is varied slightly these holes will not let in water. The borings are made so that the material may be preserved and a complete record kept of the kind of material to be expected at any given place.

If compressed air is to be used the variation in water level is determined so that the maximum air pressure required may be provided for. The only item of importance is the tide. There are practically no tunnels constructed under rivers where there is a great change in level due to storm water. The reason for such a condition is that these rivers are not deep enough for the largest boats and the river bed consists of treacherous material to a great depth which is not only difficult to work in but is likely to scour and leave the tunnel exposed. Where much work is to be done from the river surface an accurate determination of the velocity of river currents and of tides must be made. This is most important in connection with tunnel construction by the trench or the caisson method. From this data the hydraulic pressure on the side of the structure can be determined. In the case of the Harlem river tunnel the pressure on a section of the roof sunk was calculated at 375 tons.

Location Survey: The location survey consists of fixing a point on each shore in sight of each other and determining the course the tunnel is to pursue across the river. This is a tangent wherever possible but both ends of the sub-aqueous portion of the Detroit river tunnel are on curves. For the preliminary survey only a few borings are taken but for the location survey

several hundred borings may be made and test pits sunk to determine the behavior of the material when worked and to determine the amount of water likely to be met with. From the kinds of materials encountered an accurate knowledge can be gained of the geological formation under the river and the best level at which to place the tunnel. Also it can be determined whether the tunnel tubes will need more support than could be depended upon from the material through which it passes. The quantity of water likely to be encountered cannot be ascertained without pumping for a considerable time and keeping the upper part of the tube sealed. Even then, data on this are not very certain. In some cases tunnel construction has been abandoned because of the large amount of water encountered.

Securing grounds for contractor's plant: It is also a part of the preliminary engineering work to secure suitable ground for the contractor's plant and for dumping the excavated material. These details are necessary in order to permit the contractor to make his bids. The ground for the plant must be as conveniently located as possible with reference to the work. It is advisable for the engineering department to take great care that this is done for a slight additional expense in this respect may lower the cost several thousand dollars. The contractor should have access to the ground above the land portion of the tunnel in order to make openings for letting down materials, etc.

Securing grounds for dumping spoil: The material that is taken from the land portion of the tunnel should be dumped in places

where possible that it will fill up low ground and that the contractor may not only not be at any expense for the privilege but may derive some revenue from it. The spoil from the river portion should be loaded on scows and dumped from them in deep water or in places where it is needed to fill up. The spoil from the Detroit river tunnel is dumped near the work. A part of the material dredged from the river is carried down stream only a few hundred feet while the remainder is carried up the river and deposited between Belle Isle and the Detroit shore.

Plans, specifications, contract drawings: Another important part of the preliminary engineering work is the preparation of the contract drawings, contract and specifications. These must be executed to the minutest details. This is even more necessary in a piece of work of this size than in one of smaller size. A complete set of contract drawings is furnished to enable the contractor to make intelligent bids. In the case of the Detroit river tunnel four tentative methods were submitted to the contractors but the final method employed was a modification of one of these plans that was made by Mr. Olaf Hoff, of the contracting firm of Butler Brothers, Hoff & Co. to whom the contract was awarded.

Engineering work during construction: Alignment: The proper alignment of a sub-aqueous important matter. In an ordinary tunnel an error in alignment or level would merely increase the cost of thw work,but in a sub-aqueous tunnel it would probably cause the failure of the entire work. Great care is usually taken in this part of the work and because of frequent checks on the

work, errors are usually very small. The alignment of a subaqueous tunnel is simpler than that of a land tunnel for usually a clear sight can be obtained from one portal to the other. The alignment of the St. Clair Tunnel was very simple. The whole tunnel and its approaches is on a tangent. The problem was to lay off this tangent with the least possible deviation from a straight line.

At the open cut at each tunnel portal, on the edge furthest from the river, an instrument station was erected. It was necessary to locate it close to the slope in order to sight into the mouth of the tunnel. It was necessary to guard against the moving of the instrument by the slow movement of the clay in which the cut was made. To do this a brick pier three ft. square, 12 ft. deep, and capped with a cut stone block 2 ft. deep was built. The theodolite was mounted on this and a comfortable covering built over it. The instruments were large theodolites built especially for the work, one by Stackpole, of New York, the other by Troughton & Simms, of London. They had 2 1/2 in. object glasses and were reversible in the wyes. There was a clear sight from one instrument to the other. Each one was adjusted to bisect the object glass of the other at a distance of 6300 ft. It was then turned down toward the mouth of the tunnel and a Stackpole transit with shifting head was set there and adjusted until it was in line. The transit was turned to bisect the object glass of the large theodolite for a backsight and reversed to carry the line into the tunnel.

The following method was used to carry the line through the bulkhead into the compressed air chamber: A cast iron pipe one ft. in diameter and 25 ft. long was built into the center of the bulkhead and with its axis coinciding with the axis of the tunnel. At each end was a hinged glass cover protected by a hinged iron cover. This pipe was fitted with valves at each end so that it formed an air lock. Near each end were cross hairs of fine wire, mounted on a ring with vertical and horizontal adjusting screws, capable of being adjusted like the cross hairs of a transit.

To get the vertical wires exactly in line at both ends, a transit was set up outside the bulkhead and sighted through the tube. Both the iron and glass covers were open at the outer end and the iron cover at the inner end of the tube was open and a light was held behind the glass cover to illuminate the cross wires. After adjusting the wires the transit was taken inside and the outer glass door closed and the inner one opened. The transit was then set in line by means of the wires. It is seen that the sights at no time were taken through the glass doors and no errors from refraction could occur. The glass covers were to form an air tight cover and still allow the wires to be illuminated by a light held behind them. The leveling was done with ordinary levels. The method of passing the bulkhead was the same as described for the transit. Observations were made daily to determine the position of the center of the shield, and to see that the plane of the bulkhead was perpendicular to the axis of the tunnel. When the shield was found to be out of its proper position

the rams on the side toward which it was to be moved were not worked at full pressure,while those on those on the opposite side were. It was found to produce very great stresses in the shield when the rams on one side were left idle. The variation from its proper position was never more than 2 in. When the shields were 100 ft. apart a drift was run through and lined with wood. The measurements were verified through this opening and when the shields met the error in alignment was zero and in levels was 1/4 in.

Inspection: In tunneling,as in every other kind of work, the party for whom the work is being done must have inspectors to see that the contractor and his employees do the work according to specifications. These inspectors are a part of the engineering corps. It is their duty to see that the concrete is mixed in the proper proportions, the proper amount of water used, that the mixer makes the necessary number of revolutions, that concrete is not allowed to begin setting before it is used. Besides the inspectors of concrete there are many others. Some of the things to be noted inside are, the conduits, splicing chambers, water proofing, wiring, drainage, ventilating apparatus, and track laying. The inspectors report each day to a chief inspector who reports to the engineer.

Monthly estimates: Contracts of this kind are usually made to provide for a payment to the contractor of a per cent usually 80 to 85 per cent of the cost of work done and material in place each month until the amount held back reaches a certain sum and full payment after that. It is the duty of the engineers to

determine the amount due the contractor each month. The contractor himself keeps an account of all the material used and of the work done by the men. This gives him an accurate means of knowing where he can reduce costs to the best advantage.

Engineering work after construction: Inspection: After the work is completed it is necessary to go over the entire work frequently to see that there are no breaks in the lining, that the track is in good condition, that the ventilation is being properly done. A track walker performs this work. While the tunnel is new he goes through very frequently but when the first weak points are remedied it is not necessary to use such great care. It is even more necessary that all defects that might cause derailment are prevented here than on open track, for a wreck in a tunnel especially if accompanied by fire would be a very serious matter. Also a violent shock might crack the lining. The lighting is usually arranged so that if one circuit is cut out it will not leave a section of the tunnel dark but will only affect every 5th or 6th light.

Maintenance: The maintenance of the tunnel portion of a railway consists in keeping the track in alignment on curves, keeping the roadbed smooth, replacing ties and rails, renewing burnt out electric light bulbs, stopping leaks, if any occur, and other things which may come up. It is found that rails deteriorate much more rapidly in a tunnel than in open air. This is thought to be due to the action of gases confined in the tunnel. With electricity as a motive power this has been largely overcome. There are refuge niches, and in some tunnels a foot walk

along the side of the tunnel to allow workmen and inspectors to get out of the way of passing trains. In double track tunnels there are frequent cross over to allow workmen to pass from one tube to another, and to allow ventilation.

3. Drift Method: This is the method used in all land tunnels and the one tried on several sub-aqueous tunnels. An excavation is made by the workmen using picks, shovels and explosives. The space is largerin section than the completed tunnel is to be. The timber lining is inserted as soon as the excavation is made. If much water is encountered it is necessary to leave the timber lining in place and build the permanent lining inside. The space between them is filled with concrete, broken stone or clay. If the excavation is in rock the timber may be removed before the permanent lining is built. This lining consists of brick or stone built from 2 to 4 ft. thick. At the time this method was used,concrete had not come into general use. The section was usually horse-shoe shaped. The best examples of this method of construction are the Mersey, and the Severn river tunnels. In the construction of the Severn tunnel a large spring was met with and it was difficult to keep out the water with the lining used. In the first attempt to build a Detroit River tunnel by this method, water was struck which flowed with a high head and the work had to be abandoned. If the shield had been used in either case this difficulty would have been easily over-come. In the construction of the Detroit river tunnel by the trench method as was finally done no trouble came from this source. The drift method will never be used again in sub-aqueous railroad tunnels and need not be treated fully here. It is an attempt to carry land tunneling methods into sub-aqueous tunneling. It is the first method and all others are improvements over it.

Shield method: Most sub-aqueous tunnels have been constructed by the shield method. The first use of a shield was in the construction of a tunnel under the Thames river at London. This shield which was designed by Brunell was of ponderous construction and was propelled by hand with screw jacks. Modern shields are lighter in weight, usually cylindrical in form and are propelled by hydraulic or pneumatic pressure.

The St. Clair tunnel shield was the first one used in America with the exception of Beach's shield used to construct an experimental tunnel under Broadway, in New York City. The St. Clair Shield was designed by Mr. Hobson, Chief Engineer of the work. Complete working drawings of this shield are shown in the Engineering News, of November 8, 1890, and also on page 117 of Stauffer's Modern Tunnel Practice. The Shield consists of a cylindrical steel shell 15 ft. 3 in. in length and 21 ft. 6 in. in external diameter, made of steel plates one inch thick. The plates were planed to size and are 5 ft. 7 35/64 in. long and 4 ft. broad. Twelve of these plates make a complete ring, and three of these rings with a narrower one 3 ft. 3 in. in axial length make up the shell. Butt joints are used throughout, and are made by riveting angles on the interior face of the plates and then riveting the angles together. This makes a strong joint to withstand external compression. In order to leave room for the hydraulic rams, and for placing the tunnel lining, the longitudinal joints of the rear ring were made with an inner and outer splice plate, the former 2 ft. 11 1/4 in. long and 1/2 in.

thick, the latter 4 ft. long and 5/8 in. thick, each 1 ft. wide. These outer splice plates on the rear ring were the only projections on the outside of the shell, the rivets being countersunk.

The front edge of the shield was planed to form a cutting edge having an angle of 20 degrees. Two angles 3 in. by 1 1/4 in. were riveted around the inside of the shell at the rear with the 3 in. leg riveted to the shell and the 1 1/4 in. legs facing each other and 2 1/2 in. apart. In this was inserted a rubber packing strip with a cross-section 2 in. square extending entirely around the circumference of the shield. This packing was held in place by set screws. Each ring of the cast iron lining was to be bolted to the ring last completed and just in front of the rubber packing. Thus it was intended to make a tight joint between the lining and the shield and prevent mud and water from working into the shield. It was thought that the elasticity of this packing would prevent stresses due to slight variations in the castings or in the direction of the shield. Early in the work this packing strip was abandoned. The friction upon it caused it to roll out of the groove and it could not be held in place by the set screws. A steel ring of the same size was substituted and worked so well that there was no trouble from clay or water working in at this point.

The bulkhead in the shield was 4 ft. from the rear edge at the first circular joint and its edge was riveted between the angles of this joint. It was of 1/2 in. steel plate. It was

reenforced by 7 horizontal and 3 vertical stiffeners riveted to its rear face. These stiffeners consisted of plates and angles, a plate and two angles in the vertical and a plate and 4 angles in the horizontal stiffeners. These stiffeners extended 9 in. out from the face of the bulkhead. Two doors were cut in the lower part of the bulkhead, each 6 ft. high and 4 1/2 ft. wide and through these all the excavated material was passed. All around the frame of the door was a rubber packing strip against which the door rested when closed. These sliding doors could be closed by a chain. They were to be used only in case of an inrush of water but were never closed while the work was in progress. There was no provision for closing these doors in case they stuck or were wedged by the inrush of material. There should have been some means of closing them from the outside by means of a crow bar, a small lug would have been sufficient. The fact that there was no occasion for closing them is not a sufficient excuse for the absence of a means of doing so. Considering the great care and precaution taken in the details of this shield it is strange that this should have been overlooked. It was considered that as borings were taken for 8 ft. in advance of the working face the small amount of water or sand that could come through an auger hole would give the workmen time to escape and close the doors.

Twenty-four holes 13 1/2 in. in diameter were cut in the bulkhead near its circumference and to make up for the weakening, plates 1/2 in. thick and 16 in. wide were riveted to the bulkhead. These holes were to receive the hydraulic rams. Two gusset

plates were riveted to the bulkhead in front of it and to the shell. The head of the cylinder of the hydraulic ram was flanged and rested against the bulkhead. The tail of the cylinder was fitted to a ring bolted between the gusset plates. Two horizontal and three vertical partitions were built in front of the bulkhead to strengthen the shell against deformation. The horizontal partitions were used as working platforms and stopped 4 ft. in front of the bulkhead thus leaving an opening through which to throw excavated materials. The vertical partitions also stopped 4 ft. in front of the bulkhead. The horizontal partitions extended to the cutting face, the vertical partitions sloped back at a slight angle. Fourteen flat bars 7 in. x 1/2 in. were bolted to the rear of each of the vertical partitions and to the bulkhead to sustain it in case of an inrush of water or quicksand.

It was intended to have one shield built in the United States and one in Canada to avoid the heavy tariff but the American Company refused to undertake the work and both were built by The Hamilton (Ont.) Tool and Bridge works. The plates were punched and fitted in the shops and assembled at the site of the work. A cradle of wood was built to receive the shield at the bottom and skidways of 4 lines of timber 1 ft. square, 4 ft. apart were built. The shield was so built that when it rolled down the skidways to the bottom it would stop in a vertical position. Six large cables were passed around the shield, the end passing under the shield was made fast and the end passing over was given a few turns around a pile driven at the head of the skidway. A

man at each rope controlled the large cylinder as it rolled down the slope into place. The shield weighed 80 tons and it required 80 minutes to roll it in place. While the direction of the shields could be regulated by differences in pressure of the hydraulic rams on either side there was no provision to prevent rotation. The shield on the American side began to rotate from the first, the top moving toward the south until it was 20 degrees from the vertical, it then began to rotate in the opposite direction and passed its proper position. When the two shields met it had come to a position 30 degrees in the opposite direction. The Canadian shield rotated toward the south from the start and when they met both shields were in the same position, their partitions coinciding exactly. The reason for the rotation is not understood. It would be wise in future shield design to have some device for controlling this motion.

Twenty-four hydraulic jacks were used to drive the shield forward. These were spaced at equal distances around the inside of the shell and fastened to the bulkhead as was explained in the preceding paragraph. Each jack had two cylinders, an 8 in. cylinder with an effective area of 49 1/2 sq. in. for forcing the shield forward and a 2 3/8 in. cylinder with an effective area of 3 5/8 sq. in. to pull back the large plunger and leave room for a new ring of lining. With a pressure of 2000 per 1 sq. in. a force of 49 1/2 tons could be exerted by one jack to drive the shield forward and a force of 3.6 tons to draw back the head. The cylinders and head were of steel and the plunger of cast iron.

The steel head was made so that it exerted all the pressure on the 2 in. shell of the cast iron lining and this avoided all danger of breaking the flanges. The maxim stroke of the plungers was 26 in. In practice a stroke of 23 in. was used as this gave ample room to place the 18 1/4 in. ring of lining.

The shield for the Hudson River tunnel was similar in construction to the St. Clair tunnel shield. It was 19 ft. 6 in. in diameter and 10 ft. 6 in. long and was driven by 16 hydraulic rams giving a pressure of 100 tons each. There were 9 compartments each of which was separate from the others and these were air tight thus allowing compressed air to be used.

Shields may be assembled outside the shaft and rolled in place as was done in the case of the St. Clair tunnel shield, or they may be constructed in the shaft or in a special chamber made for the purpose. The latter is the usual method. This was used in the land section of the Detroit river tunnel. There were three shields. The first was semicircular and cut a passage to receive the middle wall which was to separate the two tubes. The other two were of a special design and were fitted with runners which moved in channels that had been imbedded in the upper and lower part of the center wall. For particulars see the accompanying plate.

Another type of shield is called the roof shield. A drift is run and the side walls are constructed. Then a shield of semicircular form is driven through with its sides resting on this wall. The front and rear extend beyond the supports to hold up

the earth above. Under the tail the roof of the tunnel is built and the excavation is carried on beneath the roof of the shield. This shield was used in the East Boston Subway. It is not applicable to water bearing earth or to quicksand. It works well in stiff clay.

When the upper part of the tunnel is in earth and the lower part of the tunnel in rock the following method is used: The upper part extends forward and holds up the superincumbent earth. The men do the drilling and blasting under this protection. The clay in the upper half is removed by the ordinary method of cutting into slices and loading on cars. Neither the Detroit river nor the East Boston Subway tunnel shield could well be used in connection with compressed air.

The early shields were propelled by screw jacks driven by hand power but hydraulic power soon took the place of this and will probably be used to the exclusion of all others. It offers easy control, constant pressure and freedom from danger from accidents which is not true of steam.

Since the shield is in the most critical place possible when the work is completed it is not practicable to remove it bodily. For this reason the shield is made so that the lining fits inside of it and is dismantled and left with its shell outside the lining, or if the inside is to have a concrete lining the joint between the shield and at each end and between the cutting edges of the shields in the center are thoroughly calked and they are made to serve as a part of the lining, taking the place of the case iron regiments.

Caisson Method: The name suggests that this method is similar to the familiar method of sinking shafts for piers. This is true. This method was proposed by J. F. O'Rouke. It was proposed before the trench method or roof method was used and is similar to both of these. The line of the proposed tunnel might be dredged to some extent or not. Shafts were to be sunk in the river on the line of the tunnel and about 500 ft. apart. These were to be water tight. The two ends of the shafts through which the tunnel line ran were to have sections of the wall as wide as the floating caisson, that were removable. A complete section of the tunnel long enough to reach between shafts was built and floated into place. This section had strong side walls of timber which were heavily braced and extended 5 or 6 ft. below the sides and ends of the section forming a chamber beneath the tunnel. The section is sunk into place, the walls of the shaft in which the ends fit acting as guides. When the side walls touch bottom the water is forced out of the chamber formed by them by the use of compressed air. The material is excavated from this chamber in the same way that it is done in an ordinary caisson. Care must be taken to keep the excavation even all around the outside to insure even settling of the caisson. When the section has settled to sub-grade the excavation is stopped and a foundation of concrete is made consisting of a number of piers or a solid mass of concrete filling the chamber. The connection between adjoining sections is made in the vertical shafts and this may be with or without the use of compressed air, depending on the degree of

tightness of the walls. The connection made, the shafts are removed and the tunnel tubes are covered with a layer of clay to bring the river bed to its former level or to furnish a blanket to protectthe tunnel. Large rocks are laid on top to prevent scouring and exposure of the tunnel roof. This method was used on the Seine tunnel at Paris.

Roof Method: The only example of tunnel construction by this method is the Harlem River tunnel which forms a part of the New York Subway system. The depth of the rail-base is 44.66 ft. below mean high water, and the river bed is about 26 ft. with a range of tide of about 5 ft. The material penetrated is mud, silt and sand, the latter being almost like quicksand. The river is 400 ft. wide but 610 ft. of the tunnel consists of two parallel cast iron lined tubes. The plan used was devised by Mr. D. D. Mc Bean,of the sub-contracting firm. He proposed to enclose the space in which the tunnel was to be constructed by two parallel walls of special 12 in. sheet-piling. These were cut off at the proper level and a roof consisting of three layers of 12 in. timbers placed transversely and between each two of these a layer of 2 in. plank running longitudinally. This roof was to be well calked and the material inside was to be removed either with or without the use of compressed air.

The river was first dredged so as to leave about 7 or 8 ft. of material to be removed from the chamber to be formed. Four longitudinal rows of piles were driven under the proposed tunnel

6 ft. 4 in. apart transversely and 8 ft. longitudinally. These piles are cut off, capped, and used to support the heavy roof, to support the interior bracing system; and later to be cut off at subgrade to support the finished tunnel. A platform 20 ft. wide supported on piles and parallel to the tunnel line and on both sides of it aided in the alignment of the piles and placing of the bracing.

To secure accurate alignment a timber frame was constructed to fit closely between the two rows of sheet piling to be driven, with the center line of this frame coindiding with the center line of the tunnel. The frame was built in lengths of 216 ft. floated to position, accurately aligned and sunk. Another frame was bolted to the platform leaving just enough space to receive the sheet-piling wall between them. The sheet-piling were of 12x12 inch long-leaf yellow pine 65 ft. long. Three were bolted together making a unit 36x12 in. and these were tongued and grooved by spiking 3x4 in. pieces on the edge. Pilot piles made of steel channels and plates, forming a 12x12 in. pile 60 ft. long were built. These were fitted with pipes running through to the pile point so that water could be used in washing away the materials. By the aid of these pilot piles, boulders could be detected and removed before the sheet piles were driven.

The roof was constructed in lengths of 39 to 130 ft. Six lines of longitudinal timbers were bolted to the bottom of this roof so that when it was sunk they rested on the sheet piling and on the four rows of longitudinal piles between. These rangers were 12x14 in. timbers. Small "T" irons were bolted to the outer line of

range timbers so as to cut into the sheet piling and form a water tight joint. These were later found to be unnecessary and were omitted.

The roof was covered with 5 ft. of mud, dredged from the vicinity, to bring the roof to a firm bearing and to provide against the upward force of the compressed air. The ends of the chamber were closed by bulkheads making the chamber 216 ft. long. At the center of this length a shaft 7x17 ft. was built and fitted with an airlock, and below this a rotary and a direct acting pump for jetting out materials. A shaft for taking down segments of the cast iron lining was placed near the center and the ends. The water was driven out by compressed air and the leakage was found to be small. The material inside was excavated and the tunnel lined and concreted with little trouble.

The roof was omitted in building the shore sections. The sheet piling when strongly braced were depended on. The cofferdam was pumped out and the work inside nearly finished when water broke in beneath. It was found that the sheet piling had stopped 5 to 8 ft. above bed rock and the pressure was enough to force water beneath the sheeting. The break was stopped by filling, and driving the sheet piling down.

The second half of the tunnel was built on a modification of this plan. For the heavy timber roof used in the western half was substituted the upper half of the tunnel itself. The sheet piling and bearing piles were driven as before but were cut off at the springing line of the proposed tunnel. The box thus made

was to be about 300 ft. long. The roof was built in three sections; one 84 ft. and two 90 ft. long. To erect this roof a floating box was constructed, 106 ft. long, 55 ft. wide, and 12 ft. deep. The bottom sides, and ends were of 3 inch planks, with all joints well calked. Upon the floor of this box a false floor was constructed for the upper half of the tunnel.Upon this floor the cast iron lining was erected in six foot rings, and rods and braces were used to guard against possible deformation. Suspension bars were built in for use in sinking this roof. The skew-backs were very heavy with wide flanges and outside guide flanges. This glange was drift bolted to the top of the sheeting after the roof was sunk. To do this openings were left in the concrete and the bolts were set by a diver and driven by a long follower from the boat above. An opening was left in the roof so that a diver could enter and bolt to sections of the roof from the inside. Each six-foot ring of cast iron weighed about 41,000 pounds and carried 618 cu. ft. of concrete. The calculated weight was about 50 pounds less per linear foot than the buoyancy of the empty roof chamber.

A short section of the tunnel was completed in an open cut and provided with horizontal air locks. A tight bulkhead was built some distance inshore and then the cofferdam was removed. When all was in readiness for sinking the roof section, suspension tackle was attached to the eye-bars and to heavy beams on the working platforms, water was pumped into the box in which the roof was built until its floor sank below the floor of the roof

chamber. When the clearance was sufficient one end of the box was removed and it was pilled out lengthwise and used in building another roof section. In the meantime compressed air was pumped into the roof chamber to keep out water and maintain the displacement. The roof was aligned by means of fine wires set up at each end of the tunnel section. The roof was weighted with stone, and sunk and then connected by a diver. The work was so accurately done that the connection of the first river section with the land section was made with 1 inch bolts entering 1 1/16 in. holes. To make the connection between the old and new work a large diaphragm of steel plate was attached to the end of the last roof section. This diaphragm was 23 feet 2 inches long and 8 ft. 4 in. high. Above this was another plate 5 ft. wide. These plates covered the entire end of the old chamber. A manhole 20x30 in. was made in the lower plate, to a low connection between the two chambers. The diaphragm was attached to the transverse sheeting by lag screws and a plate 14 in. wide was fitted along the sides and across the top of the high roof section to close a space left open there. This method of construction was one of the steps which led up to the trench method that will be next described.

Trench Method: The best example of this method of construction is the Detroit River tunnel now nearing completion. This will be described in detail since it is probably the first of a number of tunnels that will be constructed by this method. It has the same advantage as the Harlem River tunnel of being located with the roof only a little below the river bed and thus re-

duces grades and approach tunnels to a minimum. In fact the roof of the Detroit river tunnel is in one place 8 ft. higher than the present river bed, but this will be covered with earth and stone to protect it from the action of the current and from sunken boats.

The original plan was proposed by W. J. Wilgns, vice-president of the Michigan Central lines, and the final plans were modifications of this one proposed by Mr. Olaf Hoff, of the contracting firm of Butler Brothers, Hoff & Co. who have the contract. A tunnel was attempted at Detroit in 1872 but failed on account of the large amount of water encountered. Permission was received from the United States government to construct a bridge across the river, but the Canadian government refused this permission as long as a tunnel was considered possible. Since one has been successfully built at St. Clair, Michigan, on the same water way it became necessary to construct one at Detroit.

In general this method consists of dredging a trench across the river, sinking sections of double-barreled steel tubes and concreting them outside, pumping out the water, and concreting inside. The tunnel proper will be 8943 ft. long, the Detroit land tunnel 2129 ft., the sub-aqueous tunnel 2622 ft., and the Windsor land tunnel 3192 ft. The roof will be not more than 41 ft. from the water surface which gives more than is required by the navigation laws. The channel is dredged across the river by means of dipper and clamshell dredges. To a depth of 45 ft. it is excavated with the dipper and below that with the clam

shell. The trench is 48 ft. wide at the bottom and the sides have a slope of 1 1/2 to 1 making it about 80 ft. wide at the top when the roof of the tunnel is at the same level as the river bed. The material excavated is loaded on scows, taken away, and dumped at places in the river specified in the contract. The first plan was to use guide piles and foundation piles as were used in the construction of the Harlem River tunnel but the guide piles were dispensed with entirely and a grillage foundation. (See photographs.)

The tunnel tubes are constructed in sections 262.2 ft. long. The tubes are of 3/8 in. steel 23 ft. 4 in. in diameter and the two cylinders are stiffened and properly spaced by means of diaphragms spaced 12 ft. apart surrounding the tubes and perpendicular to them. These diaphragms are of 3/8 in. steel and are stiffened by two 3 1/2x3 1/2x3/8 in. angles extending around the circumference of the tubes where the diaphragms come in contact with them and around the outer edge of the diaphragm are two more angles of the same size. Other angles are distributed over the surface to make the diaphragms stiff. The total width of these diaphragms is 55 ft. 8 in. and the height is 30 ft. 10 in.

The sides are walled up with 3, 4, and 6 in. maple planking the thicker plank being at the bottom. The cross ribs or diaphragms and this planking form pockets in which concrete is later deposited. The ends of the tubes are closed by bulkheads well braced and calked so as to make thetubes water tight. To the

first section vertical tubes 4 ft. in diameter and 32 ft. high were built from the top of the tunnel tubes. This was to permit access to the tubes and to give an opening for pumping out water. The tubes are built complete, planked up, bulkheaded, and rings attached for fastening ropes, at the St. Clair yards of the Great Lakes Engineering works 48 miles away. They are launched similar to a boat but differing in that the tubes leave the ways broadside while a boat is launched bow first. The tubes are then towed to place and sunk. (See photographs.)

Scows firmly anchored to 25 ton concrete blocks in the river up stream are used in sinking the tubes. Four of these scows are used. They carry the derricks, air machinery, diving apparatus, hoisting machinery, etc. necessary for the work. Masts are placed at the ends of the west bound track tube and securely bolted and braced over the center line. By means of a transit on shore, the tube is accurately aligned. Divers adjust the bearing of the tubes on the grillage foundation and make the connection between the section and the one previously sunk. Each section weighs 800 tons and in order to increase the buoyancy when the tunnel tubes are full of water, four steel tubes 10 ft. in diameter and 60 ft. long are fastened to the upper side of the section. These are connected with the compressed air machinery so that the buoyancy is always under control. The tubes were sunk by opening 14 inch valves in the bottom of the tubes. When the first section was sunk there was considerable tipping due to the vertical shaft at one end. This gave an unbalanced

weight of 24 tons. When the water reached this shaft the buoyancy due to the space enclosed by it made up for this and the tubes slowly righted themselves as they sank.

The proper contact between each tunnel section and the one previously sunk was secured by having a pilot pin fit into a hole in the previous section. The connection between sections was made by divers. A sleeve fits over the joint and bolts to a flange on each tube. By means of rubber gaskets these joints are made tight and a space 3 in. wide and 18 in. long in section and extending around the tube is formed. This space is filled with neat cement grout by means of two flexible tubes which reach to the barge. These tubes are attached at the upper part of the cavity and the grout is poured into one until it rises in the other which is evidence that the cavity is full. The pipes are then unscrewed and permanent plugs screwed into the holes. The tubes are now ready for the concrete to be deposited in the pockets. When the tubes were in place the four steel cylinders on top were loosened and floated to the surface to be used on another section.

After the section is properly located on the foundation concrete is deposited in the pockets formed by the diaphragms and the planking. This is done from a scow built for the purpose. This scow has three vertical leads, each carrying a tremie tube 8 to 12 in. in diameter and 72 ft. long. The scow itself is 135 ft. long and 35 ft. wide. The hoppers at the top of the

tubes are of one 1 yard and two 2/3 yards capacity. They will deposit 30 to 36 cu. yds. of concrete per hour per tremie tube. The time required for the concrete to pass from the hopper to the end of the tube is about 5 minutes. The tubes are filled before the bottom is opened and then kept full so that there is no danger of the cement being washed out by the water. The concrete is of the proportions, 1 cement, 2 of sand and 3 of gravel or stone. The concrete assumes the section of the planking and is limited by the ribs and the cylinders of the tunnel. These are kept filled with water to give a firm bearing and for additional stiffness to resist the pressure of the concrete. The concrete is 4 ft. 6 in. thick above the steel tunnel tubes and 3 ft. thick below them. The space beneath and on the sides is filled with sand and gravel and the tubes above are covered with a blanket of sand and gravel and a layer of loose stones. This is the first time that concrete has been deposited at a depth of more than 45 ft.

After the concrete is deposited on the outside, the water is pumped out by means of a centrifugal pump placed at the bottom of the access shaft and discharging through a 10 inch pipe. When the tubes are emptied the concreting inside is begun without the use of compressed air. A ring of concrete 20 in. thick is placed inside the steel cylinder and benches are built on each side as shown in the accompanying drawings. The weight of the tubes filled with water is greater than the combined weight of the tubes

with the heaviest train possible so there is small chance of settling after the tunnel is finished. The strength of the 20 in. ring of concrete inside the steel cylinder is enough to support the weight of any train. The steel tubes have joints of double rows of 3/4 in. rivets thoroughly calked so as to be water proof.

The work inside is kept at an entire tunnel section behind the concreting on the outside so as not to disturb the radial bracing inside the tubes, and also not to injure the newly deposited concrete on the outside of the tubes. It is necessary also that the tubes be kept full of water until the concrete outside is in place or the tubes would rise by their own buoyancy.

The connection between the concrete land portion and the steel river section is made by divers. The end of the land section is constructed in a coffer dam which is removed so that the river section can be sunk and placed in contact with it.

Freezing Method: The Proetsch-Sooy-Smith freezing method has been used successfully in sinking shafts in quick sand and is proposed as a good method for tunneling in the same material. Several plans of arranging the pipes for carrying the freezing mixture are proposed. One is to drive a ring of pipes near where the outside of the tunnel section is to be and excavate within this ring. This is the method used in sinking shafts. Another proposed arrangement is to drive a central pilot tube and excavate a core then drive radial tubes from this central space.

A third method is to drive pipes at small distances over the whole face of the tunnel and thus freeze the mass more quickly. A modification of the third method is to excavate the central core and then keep the pipes against the surface. This does not require the pipes to be imbedded in the frozen material and thus increases the speed with which the digging can be done. The freezing method has the advantage of being a sure method but the principal objection to it is that it requires a great deal of time. Since the rate of construction is limited by the amount of excavation done, it would require a long time to construct a tunnel of ordinary length. A large amount of capital invested in the machinery would make a considerable item in interest and depreciation.

Sweedish Method: In 1891, a Swedish Engineer named Lillyquist proposed what might better be called a sub-aqueous tubular bridge than a tunnel. His plan was to build steel tubes 100 ft. long and let the ends rest on piers near the bed of the river. The tubes were to consist of two shells, an inner iron and an outer steel shell, well calked so as to be watertight. Between these shells was to be a space large enough to hold enough concrete to give the tubes a firm bearing on the piers when the tunnel was empty. The tubes were to be securely anchored to the piers and the buoyant effect of the water was expected to support practically all of the dead load. The tunnel was to be about 4 miles long and was to con ect the cities of Helsingborg, Sweden, and Elsener, Denmark, passing under a navigable channel.

The cost was estimated to be between $3,250,000 and $4,375,000. The scheme was never put into practice for the reason that the exposed position of the tube left it liable to damage by tides, storms, and sunken ships.

4. Linings: Since portions of a sub-aqueous tunnel are likely to be in a semifluid material it is necessary that a lining be designed strong enough to withstand great external pressure. Also the lining must be permanent since it would be impracticable to replace a section of it at any time. The principal properties that the lining for a sub-aqueous tunnel must have then are, strength to resist external pressure, durability and impermeability. Timber lining could never be used. The only kinds of lining used are cast iron, steel, concrete, and brick.

Cast Iron: Most recent tunnels constructed by the shield method are lined with cast iron. Since the lining of one of these tunnels differs from another only in the minor details it will be sufficient to describe a typical case and then point out differences in other tunnels. The St. Clair river tunnel was the first iron lined one constructed in America, and it willbe described. The lining is 21 ft. in outside diameter and 2 inches thick. A complete ring consists of 13 segments each 18 1/4 in. wide, and 4 ft. 11 15/16 in. long measured on the outside curved surface, and one small key segment 9 7/8 in. long to fit in at the top. The plate of the segments is 2 inches thick, the flanges for the circumferential joints are 2 3/8 in. thick. The flanges for the radial joints are 2 3/4 in. thick at the base and 1 5/8 in. thick at the point. Through each circumferential flange

are cored 12 one inch holes, spaced 4 1/2 in. apart, and bosses 7/8 in. high, and w in. in diameter are cast on the inner surface of the flange to compensate for the weakening caused by the cored holes. Each radial flange contains four bolt holes spaced 3 inches apart. A 1 1/2 in. hole was cored through the shell of the segment and compensated for by a 3 1/4 in. boss. This hole was to admit grout which formed a 3 in. lining outside the lower half of the tunnel between the cast iron and the clay. It required 56 bolts 7/8 in. in diameter and 5 7/8 in. long to bolt the segments of one ring together and 157 bolts 7/8 in. in diameter and 8 in. long to bolt one ring to the preceding ring. All the bolts were of mild steel and had square heads and hexagonal nuts. The nuts were screwed up against a wrought iron washer 1/8 in. thick and 1 7/8 in. in diameter. Part of the bolts were made at the Grand Trunk shops at Hamilton, Ontario, but most of them were purchased in the United States.

For the radial joint the surfaces were planed and a packing piece of seasoned white oak 3/16 in. thick was placed between them. These are sawed to exact size and holes bored in them 1/4 in. larger than the holes in the casting. After bolting in place, this wood packing absorbs water from the surrounding wet clay and swelling closes the joint tight. There is some question as to the durability of this packing. It is doubtful if under such high pressure the wood will absorb enough moisture to preserve it from decay. This can only be determined by time. These joints can be calked with lead wire or similar material if they show signs of decay.

The circumferential joints were made with a layer of P and B roofing as a packing and the faces of the flanges were not planed. This P and B roofing consists of coarse canvas covered with asphalt. It is made by the Standard Paint Company, of New York City. To provide for stopping any leaks that may occur in these joints the inner edge of the flange is cut away leaving a groove 2 in. deep and 1/2 in. wide around each circumferential joint. This may be calked in case leaks occur. Since the completion of the work a number of these joints have been calked and the tunnel is almost perfectly water tight.

About one-third of the castings for the lining were made at the Grand Trunk shops at Hamilton, Ontario, and the remainder by the Detroit Wheel and Foundry Co. The castings were of high grade iron. The mixture in the cupola at Hamilton was 80 % old car wheels and 20 % Scotch pig. At the Detroit works some southern iron was used in the mixture. For the inspection of the castings, iron templates 1/4 in. thick with openings to test the size and thickness used. The maximum excess allowed over specified measurement was 1/32 in. The variation in weight was from 1000 lbs. to 1050 lbs. The weight of the lining is 9333 lbs. per linear foot of tunnel, or 56,000,000 lbs. in all.

The castings were delivered to a machine shop on the site of the work and the radial faces planed. To facilitate the work a planer with two tables and three beds was provided. Thus while one table full of segments was being planed, the segments could be bolted on the other table. Each table held nine segments

which were placed side by side, convex surface down, and both ends planed at the same time. From 90 to 99 castings were planed in a day.

The working drawings call for a plane of the face of the radial flanges to be tangent to a 3/16 in. circle whose axis is the center of the tunnel. This is to make the faces fit against the 3/16 in. block of wood. Since this makes the difference in width of outside and inside of joint only 1/100 of an inch more than if radial joints were used, this fine discrimination is not necessary. After being planed the segments were heated in a wood fire to 400 degrees Fahrenheit, and were then dipped in melted pitch. The wooden packing pieces were also dipped in melted pitch before being used. The segments were taken into the tunnel as needed.

To place these heavy segments in place a special crane was designed by T. C. Teiper, Chief Engineer of the Hamilton Tool and Bridge Works. It consists of a small crane mounted on a shaft at the center of the shield. This shaft being supported by plates and channels bolted to the bulkhead stiffeners. By means of worm gears, the head which picked up the casting could be moved toward or away from the shield, toward or away from the central shaft, and rotated on this shaft. By these three motions a section could be placed in any position quickly. A cast iron counter weight helped to raise the segment. It required 45 minutes for 15 men to place a ring in place and bolt it enough to hold it. The rest of the bolts were placed in by men who followed and worked on light staging. The lining began with the center segment at the bottom and continued upward, a segment being

placed alternately on each side until the key was reached. This was held in place by the crane while the wooden packing was being driven in on each side and then it was bolted. The bolting was done with ordinary wrenches. The faces of the flanges of the key section were parallel and vertical when the key was in place at the top of the ring. This was necessary in order that it could be placed from beneath. This also necessitated some variation in the upper flanges of the two segments adjoining the key segment. Instead of being in planes tangent to a 3/16 in. circle at the center of the tunnel they were vertical when in place and in planes tangent to a circle at the center 10 1/4 in. in diameter. The last ring was of special castings from measurements taken after the other two rings were in place.

When the entire cast iron lining and the 3 in. ring of cement outside were completed the tunnel was carefully cleaned and the lower half was lined with brick laid in cement mortar to a thickness equal to the depth of the flanges, and brickwork was laid to receive the permanent timber as shown in the accompanying drawing of the cross section of the tunnel. This brickwork and the points of the flanges which were just flush with it were then covered with a coat of neat cement mortar 1 in. thick. This was to protect the iron from corrosion due to brine, dripping from refrigerator cars. The upper half of the lining was cleaned and given a coat of asphalt paint.

The key section which started directly over the center line of the tunnel had moved a distance of 16 in. to one side in one of the headings when the tunnels met. This may have been due to

the nuts being turned up in the same direction or in the manner in which the segments were placed. If the first one was always placed on the right before the corresponding one was placed on the left, there would be a tendency for all looseness to be taken up in the same direction.

This description of the St. Clair tunnel lining will apply to any other cast iron lining except in minor details. Some differences to be found in other tunnels will be noted here. The Spree river tunnel, at Berlin, Germany, has an outside diameter of 13.12 ft. The lining is of cast steel and consists of 9 segments and a key piece. The rings are 2.13 ft. and 1.64 ft. wide. The case steel lining is coated inside and outside with cement mortar.

The Blackwall tunnel, under the Thames, has a lining whose outside diameter is 27 ft. There are 14 segments to a ring, but they are twice as heavy as the segments of the St. Clair tunnel lining. Each of the segments of the Blackwall tunnel weighs one ton. Two hydraulic hoists were used to put them in place. There is a lining consisting of brick laid to a depth of 14 1/2 in. inside of the cast iron lining. Although this is a highway tunnel it is interesting from the fact that it is the largest cast iron lined tunnel ever constructed.

The Penn. R. R. East river tunnel has a cast iron lining of 11 segments and a key, and each ring is 30 in. long. The flanges are 11 inches deep. Outside of this is a layer of grout about 3 in. thick, and inside is a lining of concrete 22 in. thick.

There are concrete benches on either side of the track 3 ft. 8 in. wide and in these are conduits for telephone, telegraph, and power wires. The lining for the Penn. North River tunnel is like this East River tunnel lining except that as originally designed there was to be a cast iron screw pile under the tunnel and connected to the lower segments. This pile was to be 27 in. in diameter and two special segments in two adjoining rings were to be constructed to form a connection between the screw pile and the cast iron lining.

The lining for the Harlem river tunnel consists of two cast iron cylinders 15 ft. in diameter and 12 1/2 ft. apart center to center. This causes the cylinders to intersect. A special lining is constructed between tubes and in this are carried drains and ducts. The case iron of the cylinder is only 1 in. thick but this is covered on the outside with concrete of a minimum thickness of 1 ft. 6 in. Thus the cast iron serves as a form for the concrete, as a stiffener to the cylinder, and as water proofing.

Cast iron gives a rigid and durable lining but its cost is very great. It is probable that with the more improved methods of sub-aqueous tunneling, and the advances in the use of concrete that material will largely replace all ot ers for tunnel linings.

Steel: Steel alone has never been used for sub-aqueous tunnel linings. This is probably due to the great cost which would be more than the cost of cast iron. The Berlin tunnel under the Spree, was lined with cast steel segments as described before

and between the rings of cast steel lining was bolted a flat circle of steel plate extending outside the shell to give additional rigidity to the tube. This steel was backed up by cement grout rammed in after each ring was placed.

In the sub-aqueous portion of the East Boston Extension of the Boston sub-way steel plate ribs were bedded in the concrete to give additional strength to the lining. A cast iron shell of flanged and bolted segments was also used to keep out the water when water bearing material was passed through.

The Seine river tunnel and the Detroit river tunnel have in their sub-aqueous portions complete shells of riveted steel plate. This shell for the Seine river tunnel is large enough to enclose a double track railroad tunnel but in the Detroit tunnel each track is in a separate tube. The tubes are of 3/8 in. riveted steel plate and 23 ft. 4 in. in diameter. They are fastened rigidly together and strengthened by steel diaphragms 12 ft. apart. These steel shells are afterward covered with a coating of concrete which is 4 ft. 6 in. thick on above and three feet thick below the steel shell. There is also a concrete lining 20 in. thick inside the steel shell. The steel is intended to serve as a form for the concrete and as a permanent water proofing layer for the sub-aqueous portion of the tunnel. This tunnel will be discussed under concrete linings.

Brick: Brick is used in connection with cast iron for lining in several tunnels but the two principal tunnels where it was used exclusively are the Mersey and the Severn tunnels. These tunnels were finished the same year 1886. They are both double

track tunnels with single tubes. The lining is 2 ft. 3 in. in most places but at times it was considered allowable to diminish this slightly while in one place the pressure was so great that it was necessary to make the lining 4 ft. thick. Brick is probably the least efficient of materials for sub-aqueous tunnel linings on account of its not giving stiffness to the tunnel, and not being waterproof.

Concrete: Concrete is coming to be most common material for sub-aqueous tunnel lining. It has the advantage over cast iron of being less expensive,and over brick of being more easily placed and being stronger. It is used in a variety of ways, in connection with cast iron to strengthen it, in connection with steel tubes which serve as forms and water proofing and with steel ribs which give strength and stiffness. These will be described separately.

In the Harlem river tunnel the cast iron lining 1 inch thick is not strong enough to withstand the external pressure and the jar due to passing trains. There is no concrete placed inside the tubes for a lining but concrete does form a support fot the longitudinal timbers and ties in the invert. Forms were made around the tunnel tubes and concrete was deposited on the outside of the cast iron lining and completely enclosing it. The minimum thickness of this concrete was 1 ft. 6 in. and the thickness at the top of the tubes is 2 ft. 6 in. Steel reenforcement rods are placed in the concrete in planes perpendicular to the direction of the tunnel.

Both the East river and North river tunnels of the Penn. R. R.

are of cast iron lining with a ring of concrete two feet thick inside. This gives a greater rigidity to the section and prevents corrosion of the cast iron lining. There is also a thin layer of cement grout outside for protection to the iron. This grout is forced out through holes cored in the cast iron segments.

The East Boston Extension of the Boston Sub-way has a horseshoe section with a clear width of 23 ft. 4 in. and a clear height of 20 ft. 6 in. The crown and sides consist of a concrete shell 2 ft. 9 in. thick and the invert of concrete 2 ft. 0 in. thick. In water bearing material this shell was tightened and reenforced by a cast iron shell of flanged and bolted segments having steel plate ribs imbedded in the concrete with cement grout forced outside the cast iron shell.

The lining of the Detroit river tunnel is essentially of concrete. Since the land portion is constructed by means of shields it may be included under sub-aqueous tunneling. One shield cuts a passage way along the center line of the tunnel. The center wall 4 ft. thick is built in this space. A form faced with sheet steel and curved at the top is used to give the correct shape to the center wall. These forms are moved along as each section is completed and are used many times. Two side shields as shown by accompanying diagrams follow, one on either side and cut out the area required for the finished tunnel. The concrete lining for these is built in the same manner as that for the center wall. The crown and outside walls are of concrete 2 ft. 6 in. thick and reenforced with steel bars when considered advisable by the engineer.

The river portion of the Detroit tunnel is constructed in a different manner. This was described under the trench method of tunnel construction. After the steel tubes are in place, concrete is deposited around them in the pockets formed by the transverse steel ribs. This concrete is 4 ft. 6 in. thick above and 3 ft. thick below the steel tube. Inside this shell is a ring of concrete 20 in. thick. This ring alone is sufficient to support the weight of any train but the steel shell is necessary to furnish a form against which to place the concrete and to serve as a water proofing layer. The concrete outside protects the steel from damage. Gives additional stiffness and overcomes any buoyancy. There is no reenforcement in the outside concrete but steel rods 1 in. in diameter are placed 18 in. center to center in the inside lining of concrete. This concrete consists of a mixture of 1:2:4,and the concrete outside is a 1:3:6 mixture of cement, sand, and gravel.

5. Materials encountered: Rock: When the entire section of the tunnel is to be constructed in solid rock without vertical seams the drift method can be used. The material may be worked in the same way as a land tunnel but care must be taken that there are no breaks in the rock to allow water to enter. The part of the English Channel tunnel which was excavated was in chalk which worked easily and carried very little water. When there are seams in the rock it is necessary to keep bags of sand, sawdust, and quantities of clay on hand to stop the inflow of water. Small drill holes should be driven in the advance heading to determine the nature of the rock and prevent a sudden inrush of water. Com-

pressed air should also be used to keep the water out. This would be impossible if large quantities of water were met in the construction of a tunnel more than 100 ft. below the water level, since this is the limit of pressure under which it is possible to work.

When the upper part of the tunnel is in clay or other soft material, and the lower part in rock as in the case of the North river tunnel of the Pennsylvania R. R., at New York City, a roof shield is used. The upper part is excavated by the ordinary method and the rock is drilled and blasted under the protection of the protruding roof of the shield. This may be done either with or without the use of compressed air. As a rule it is not safe to use explosives in a compressed air chamber, especially if the chamber is small.

Boulders: When the material penetrated contains large boulders scattered throughout a bed of clay, the work becomes difficult. The clay makes it necessary to use a shield while a boulder may at any time cause great damage to the cutting edge of the shield. If the shield passed just below a boulder weighing several tons, the weight on the shield would cause large stresses and even might cause collapse without any warning. Even if it does not injure the shield it may injure the lining at a subsequent time. If only a few boulders are encountered they may be dealt with by the means at hand without any special apparatus. Those whose whole volume is included in the section excavated may be split up, if not too hard, and carried out on cars with the clay. If they are of very hard rock it may be easier to dig a pit in the bottom of the excavation and roll the stone into this. When the boulder

protrudes into the excavation from the side or bottom, it may be trimmed off by the use of feathers and wedges, but when it is above the entire boulder should be removed and the hole back-filled with clay.

Clay: The ordinary clay met with in tunnel work is a tough, compact, blue clay. If it is formed by the decomposition of rock in situ it is comparatively homogeneous. If it is formed as a part of the ground moraine of a glacier it may contain boulders, pockets of sand, or water, and gravel. Clay was formerly excavated with a sharp pointed spade, with axes, mattocks and long pointed shovels, but during the construction of the St. Clair tunnel a new instrument took the place of all of these and has been used in all tunnels since that time. A flat bar, sharp on one edge is bent in a semi-circle. Eye holes are formed on the ends and short wooden handles similar to those used on a shovel are inserted. One man grasps these handles while another forces the knife into the clay. The first man draws the knife thru the clay cutting out a half cylinder about 3 ft. long. The second man catches and throws this down in the car. The clay in the St. Clair and Detroit river tunnels was very tough and would sustain its own weight in long slabs. This device was invented by a workman in the excavating gang. Since the entire section of the tunnel must be advanced as one

heading the progress of the work depends on the speed with which this can be advanced. It seems that some mechanical device might be made to slice the clay much more rapidly than it is done by hand and thus increase the rate of progress of the work.

Quicksand: This is without doubt the most difficult material through which to drive a tunnel. Two methods of attack present themselves. One is a water tight shield with a bulkhead across its front end made up of horizontal timbers each of which can be removed separately. The air pressure inside is kept at sufficient height to balance the head of water in the quicksand. The lining is put in making a close joint between it and the shield. This was described in the description of the shield method in connection with the St. Clair River tunnel. The boards in the bulkhead are taken out one at a time beginning at the top and the material excavated. The board is then moved forward. When the bottom board has been moved the same operation is performed again beginning with the top. Care must be exercised in keeping the pressure at the proper height. This is about equal to the head at the top of the shield. The pressure at the bottom of the shield is more than this but if the air were kept at high enough pressure to balance this there would be danger of a blowout at the top of the shield.

The other is the freezing method proposed by Charles Sooy Smith. It has been used successfully in shaft sinking but never in tunnel work. Its principal draw back is the large amount of time required to get the material in condition for excavation.

This method is fully described under the head of Freezing Method earlier in this thesis.

Water pockets: In glacial deposits and in material made up of several layers of rock there are likely to be water pockets of greater or less size. It is difficult to determine the location of these pockets and the head with which they are likely to enter. One precaution always to be observed in suspicious material is to bore holes about 1 1/2 in. to 2 in. in diameter in the working face to a depth of 7 or 8 feet. This will show where pockets or springs are and will allow the workmen to escape before the shield could be filled. A stream of water from one of these pockets will sometimes enter with a great head, sometimes even higher than that of the water in the river above. As it continues the pumps may become able to handle it and as the pocket becomes smaller and the discharge less the shield may be entered and the opening sealed up with clay. It is not always easy to tell when a water pocket is struck and when it is a spring. If small pockets have been struck before it is taken for granted that all are of this kind.

Springs: Before the common use of shields came into vogue it was usual to construct sub-aqueous tunnels by the drift method as other tunnels were constructed. Great difficulty was found in this method because of encountering large springs. The ordinary timber linings were not able to stand the pressure and could not be made water tight. The Severn river tunnel begun in 1873 occupied 13 years in building due largely to a single

large spring encountered. This broke in so suddenly that the men were barely able to escape and had no time to close the bulkhead doors. The distance to these doors was so great that it was impossible for a diver to drag a long air hose in to them. A device called the Fleuss diving apparatus was used. This consisted of a receptacle which the diver could carry with him. It generated enough oxygen to last a man about two hours. By means of this device the bulkhead door was closed at two different times. The head of this spring was much higher than that of the river. The first attempt to build a tunnel under the Detroit river at about the same time was abandoned because of the frequency of springs and the head of water they had. When the tunnel was finally abandoned and the shafts were allowed to fill the water rose several feet higher than the level of the river.

Gravel: The principal difficulty in driving a tunnel through gravel is that is is unable to hold air. Gravel usually contains water and may be said always to carry water when located under a river. An interesting fact in this connection is that in the construction of the Northwestern Passenger Depot in Chicago, where the pressure used in the caissons is 9 lbs. per sq. in. above atmospheric. When gravel was struck the air began coming up at a distance of 3/4 mi. away. When this happens beneath a river where the blanket is only about 15 ft. thick, it is evident that the work is both difficult and dangerous. It was under circumstances similar to this that the air blew out a hole in the river bed carrying a workman out with it. This was in the construction of the Hudson River tunnel. The best remedy

for this when possible is to construct the tunnel by the trench or caisson method. When gravel is encountered in the land portion of a sub-aqueous tunnel this is impossible and the engineer must devise means to carry the work on successfully. It is possible that the face could be plastered with soft clay, then the men be removed from the air chamber and a high enough pressure put on to drive the clay into the gravel. This could then be dug off and another layer forced in. This would be very slow method and only applicable when the distance through the gravel was small. If the water was not flowing to a great extent and the gravel did not contain large enough stones to interfere with the pilot tube the freezing method might be used.

6. Foundations: Most sub-aqueous tunnels are so constructed that the weight of the section is less than the weight of the section is less than the weight of a corresponding volume of the surrounding material. If the difference between these two weights is small there is very little bearing on the soil and no foundation is necessary. On the other hand if the material is soft and the weight is great, some sort of foundation is necessary. Three kinds of foundations are used; timber piles, cast iron screw piles, and grillage.

Timber piles: The foundation for the Harlem River tunnel was of timber piles. Four rows were used. The piles were spaced 6 ft. 4 in. transversely and 8 ft. longitudinally. They were used in the first place to support the roof and were later cut off at sub-grade and used as foundation piles. When a shield is used to drive the tunnel openings may be left in the bottom for driving

down foundation piles in soft material. The allowable load on a pile driven to refusal with a 6000 lb. hammer is ordinarily taken as 19 tons.

Screw-pile foundation: This type of foundation was planned for the Battery Tunnel but it was used only in a small part as it was found to be unnecessary. These screw-piles were cast iron cylinders 27 in. in diameter and fitted with a spiral screw at the bottom. They were sunk after the lining was in position. An opening large enough to receive a pile was cast in special segments of two contiguous rings of lining. The piles were screwed down in a hole previously made for them by a pilot pile. When the pile was down to rock the upper 12 feet was filled with concrete. The piles were spaced 15 feet apart and a single row on the center line of the tunnel was provided for.

Grillage: This foundation was used to support the river sections of the Detroit River tunnel. One grillage was made to support the ends of twocontiguous tubes. Each grillage was 42 feet long, and 38 feet wide and consisted of two 12-inch I beams 42 feet long and 12 12-inch I beams 38 feet long. These beams were web connected and had their upper and lower surfaces flush. At the corners are short 6x6 inch angles to which are bolted 8x8 inch timbers 6 feet long sharpened at the lower end, projecting 5 feet below the bottom of the grillage. When the grillage is ready to put in place it is suspended under the barge by rods 1 inch square and in 20 foot lengths, fastened to the corners of the grillage. The upper ends of the rods are fitted with long threads and are held by short cantalever arms extending

over the sides of the barge. Since the grillage is 38 ft. and the barge only [illegible] these beams must extend over the sides of the boat in order to have the rods vertical. The screw threads are for accurate adjustment. The grillage piles are driven down about 5 ft. and concrete is deposited in the spaces between the I beams. This concrete is leveled off by divers a little below the top of the I beams so as to give a firm bearing for the tunnel tubes.

7. Water proofing: Coatings: There are several ways of making concrete partially impermeable to water. The two principal methods are by water proof coatings on the concrete and by treatment of the concrete in making it. The simplest coating is a layer of neat cement mortar about 1 inch thick placed on before the concrete becomes dry. It should be spread on as soon as the forms are removed. European engineers deem it necessary to use sheet-steel for cement pipe and standpipes with a head of over 50 ft. The steel is very thin and is placed on the side from which the pressure comes. In the sub-aqueous section of the Detroit tunnel the steel tubes with calked joints are deemed sufficient water proofing.

The most common practice is to use some kind of asphalt coating, either alone or with tarred or asbestos felt. In the latter case the felt is laid to break joints and the asphalt is spread under between and over the felt, and the whole is then covered by concrete. There are usually three to six layers of felt, and the asphalt is always of the best grade of Bermuda or Alcatraz lake-asphalt. The durability of this water proofing

is unknown though it is extensively used in subway work. When asphalt alone is used the concrete surface is first plastered with a rick of mortar, and the asphalt is mopped on to a thickness of 1/8 inch, and then plastered over before the remainder of the concrete is deposited. Asphalt mastic is usually laid directly on the concrete to a depth of about 1/2 inch and is then covered directly by the concrete.

Treatment of concrete: A number of experiments have been made in producing impermeable concrete by determining a mixture of cement and aggregates that would resist the percolation of water. The minimum permeability is found in mortars where the proportion of medium sized grains is small, and the coarse and fine grains are about equal to each other. Mixing slaked lime with the cement also helps make it water proof. Silicate of soda, soap and alum are used. Since the last method of water proofing is seldom if ever used in tunnel work it will not be described in full.

8. Drainage: Amount of water to be removed: The capacity of the pumps must be such as to remove the maximum amount of water that may reach the tunnel in a given time. The rails must not be flooded at any time and water must not remain in the tunnel for a very long time. Even when the tunnel is made as nearly water tight as possible there is a certain amount of leakage to be taken care of. To this must be added the quantity of water in the open cut that will reach the sumps at the portals. The capacity of the pumps for the pumps at the portals must be equal to the maximum amount of water that will fall in the lower part

of the open cut in a given time. This quantity may easily be calculated by having known the width and length of this area and the maximum depth of rain fall in that locality in the time it would take the water to flow from the farthest point of the cut. The water beyond the open cut should be led off in the general drainage system of the locality so as not to require larger pumps than is absolutely necessary.

Open cut: The slopes of the open cuts may consist of a series of terraces each containing a trench parallel to the track. These trenches hold the water during a heavy rain and are connected by pipes so that their contents may be let into the sump below and pumped out at leisure. This reduces the necessary size of the pumps very much and thereby lessens the cost. Any obstruction that will prevent the water from the farthest part of the open cut from reaching the sump in a short time would make the size of the pumps less. The maximum rainfall per minute for a short time would be much greater than that for a longer time. The advantage of having flat grades and obstructions to form pools and thus make the velocity flow less, can readily be seen. When possible the sump should be made large. This will be kept emptied at ordinary times and during a rain the capacity of the pumps will only be such as to carry the difference between the amount of rainfall and the capacity of the sump. These precautions lessen the cost of the pumping plant since they make smaller pumps necessary and keep the pumps working a larger part of the time. It is practically necessary to keep up steam and have a full force

of men in the plant at all times so no additional expense is caused by making the actual working time much longer than the actual time of rainfall.

Drain pipes: The water in the open cut flows upon the surface. The water inside the tunnel may flow down a trough between the rails or it may be led at intervals into a cast iron pipe imbedded in the concrete at one side of the track, as in the case of the Pennsylvania Railroad North River tunnel. These pipes are designed to carry only the leakage which is made as small as possible. During construction it is sometimes considered best to run a drainage drift through first. This is made when the tunnel is to be constructed by the drift method and is placed a few feet below the position intended for the finished tunnel.

Pump house and pumps: A pump house should be located at or near each tunnel portal. This is the most economical location because the largest amount of water is to be taken care of here and this is the best location for having the pipes which let the water, from the retaining trenches along the slope of the open cut, to the sumps. Pump houses should be located at the shafts on each side of the river near the water's edge. These should connect with the sumps in the sub-aqueous portion of the tunnel. The pump houses should be separate in every respect. If the pumps are run by motors they should be on separate circuits. The pumps should be duplicate in each pump house so that in case one became disabled the tunnel would not become flooded. If the plant is run by steam the boilers should be kept steamed up at all times or in readiness for firing at short notice. If electric

motors are used the connection between the pumps and the power house should be separate from each other and they should be tested every day to see if they are in good order. If gasoline engines are used to run the pumps, they should be started every day to make sure that they are in good order. The same engines may be used to run the pumps that run the fans. In case the maximum capacity of the engines is required for pumping the ventilation may be neglected for a time. There is little necessity for ventilation in a tunnel where electric motive power is used and separate engines to run the fans would not be required.

Sumps: The number, arrangement, and size of sumps should be such as to give the greatest facility in handling the water. In the Detroit River tunnel there are five sumps, one at each portal, one at each river shaft, and one in the lowest part of the sub-aqueous portion of the tunnel. This places the largest quantities of water at the portal where they can be best taken care of. The next largest at the river shafts which is the most convenient place and only a small amount will be collected in the middle sump on account of the thorough calking of the joints of the steel tubes and also because of the thick coating of concrete both inside and outside. These sumps are built below the track and across the entire section of the tunnel. The middle sump of the Detroit river tunnel consists of 4 cylindrical steel tubes 7 ft. in diameter lined with concrete 12 inches thick making them 5 ft. in diameter. They are 41 ft. long and extend perpendicular to the center line of the tunnel. They are connected at one end with a well 4 ft. in diameter which extends 4 ft.

below the bottom of these tubes. It is from this well that the pumps take the water. The tubes have a slope of 1 in. in 10 ft. towards the well. The capacity of this sump is about 27,000 gallons. The capacity of the shaft sumps is 21,000 gallons each and of the portal sumps is about 50,000 gallons each. The pump chamber is near the center and connected with the sump chambers at the bottom. The motor chamber is just above. The pumps are all run by motors in this tunnel.

9. Sections of tunnels: Dimensions: Sub-aqueous tunnel tubes have been constructed both with single and double railroad tracks. It has been found more economical to construct each tube for a single track than for two tracks because of more material required for the greater span of arch for the roof. The top clearance is nearly the same for all tunnels for ordinary railway traffic and slightly less for city railways. In the following table is given some of the dimensions of the most important modern sub-aqueous tunnels.

Details: The details of the Detroit tunnel will be described. These are typical of modern tunnels and represent the latest arrangement and improvements of modern tunnel practice.

The tunnel carries 44 separate conduit ducts. These are of the single hole style 5 in. square and are arranged as follows; twenty are placed on the side of each tube nearest their partition wall and under the concrete bench. These carry telephone, telegraph, and signal wires. Twelve are carried on the outer side of each tube and these carry the power wires. Thus the high tension and low tension wires are separated. These ducts are laid with the joints wrapped in burlap soaked with a mixture of cement and water to make them water tight. They are bonded to gether by means of bars extending across the row and ending in a split and bent end which bonds them to the concrete in which they will be imbedded.

Splicing chambers are spaced 400 ft. apart and 8 ft. long, 2 ft. 8 in. wide. The cover is of cast iron and is flush with the top of the bench. The sidewalks consist of benches built of solid concrete 5 ft. 3 in. above the top of rail and 3 ft. 10 3/8 in. wide. This leaves a clear space between benches of 13 ft. on tangents and greater on curves, the width of the bench being lessened there. A hand rail of 1 1/2 inch gas pipe is securely fastened to the wall 4 ft. above the surface of the walk. The electric conductor is a third rail of the under contact type and is placed on the outer side of the tubes near the power conduits, and so that the shoe on the locomotive is on the right side.

The reenforcement in the inner wall of the splicing chambers

consists of old rails placed longitudinally. The longitudinal reenforcement in the 20 inch ring of concrete inside the steel tube is 1 inch diameter rods spaced 18 in. apart. These are only to be used when specified by the engineer and are to be paid for at the contract price. Ladders are spaced 50 ft. apart on each side of the tunnel and are staggered. They consist of 1 1/2 inch gas pipe 3 ft. long imbedded in the concrete at both ends and spaced 19 inches apart. A cavity in the side of the bench received them so they do not decrease the clear width of the tunnel. These ladders are to make a way of getting from the track to the sidewalk. Hand holes for lighting are spaced 40 ft. apart on each side of the tunnel and staggered. All exposed corners are rounded off to 1 inch radius unless otherwise specified. Cross passages between tunnel tubes are spaced 200 ft. apart and are to be 6 ft. 9 inches high and 2 ft. 6 in. wide. They are fitted with doors of 3/16 in. plates stiffened with angles. These doors are just above the level of the sidewalk. The track rail is 6 inch 100 lbs. per yard. The tunnel is lighted by incandescent electric light bulbs. These are so arranged that several circuits overlap and if one circuit is cut out only an occasional light is turned off in a given part of the tunnel instead of a section being in total darkness. The traffic being constant in direction in each tunnel and the shafts a little over 1/2 mile apart, natural ventilation is depended upon.

Shafts. There are two permanent shafts in the Detroit river tunnel one near each bank of the river. These are fitted with stairs so that they can be entered from the top. The shafts

are oval in section, being 13 ft. 6 in. wide on a line parallel to the direction of the tunnel and 16 ft. 6 in. on a line perpendicular to this. The walls of the shaft are of concrete.

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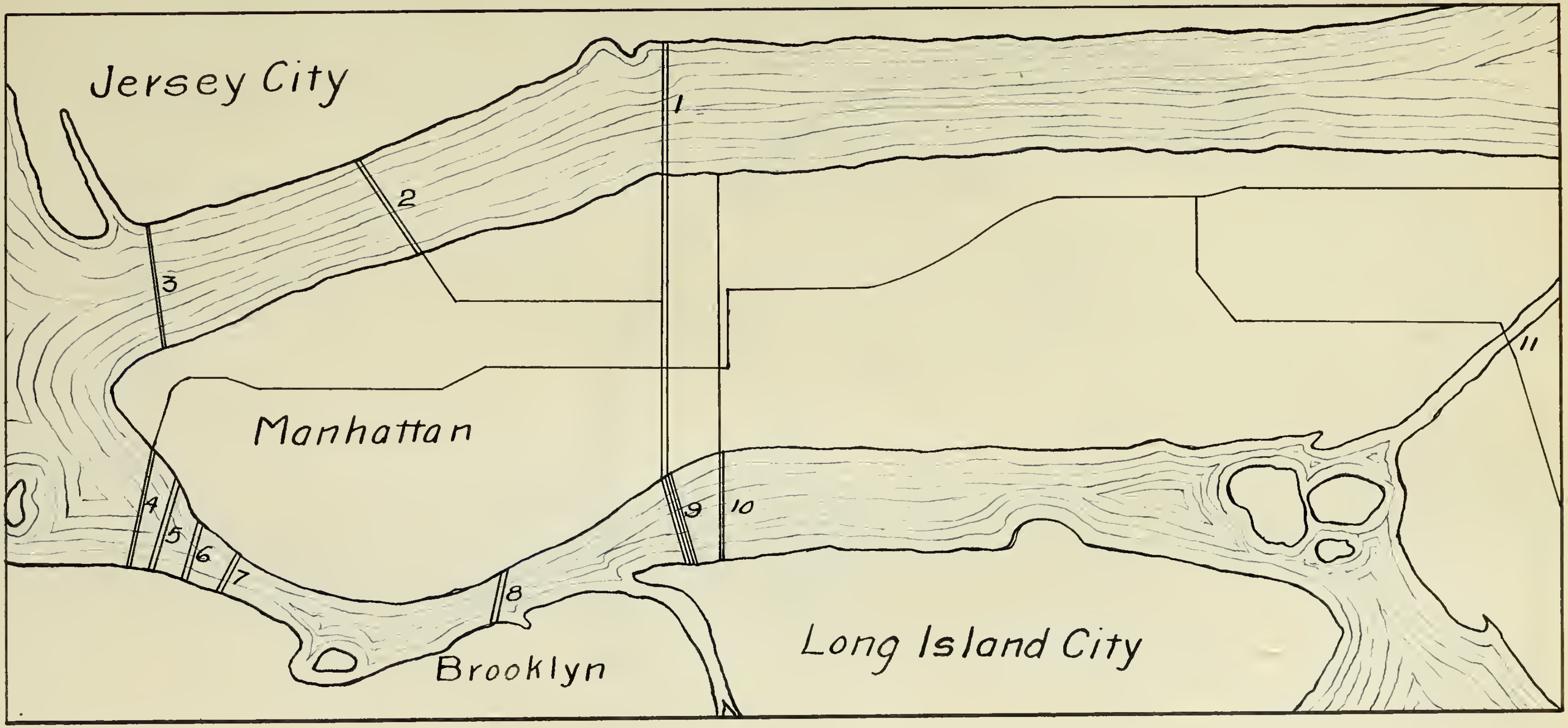
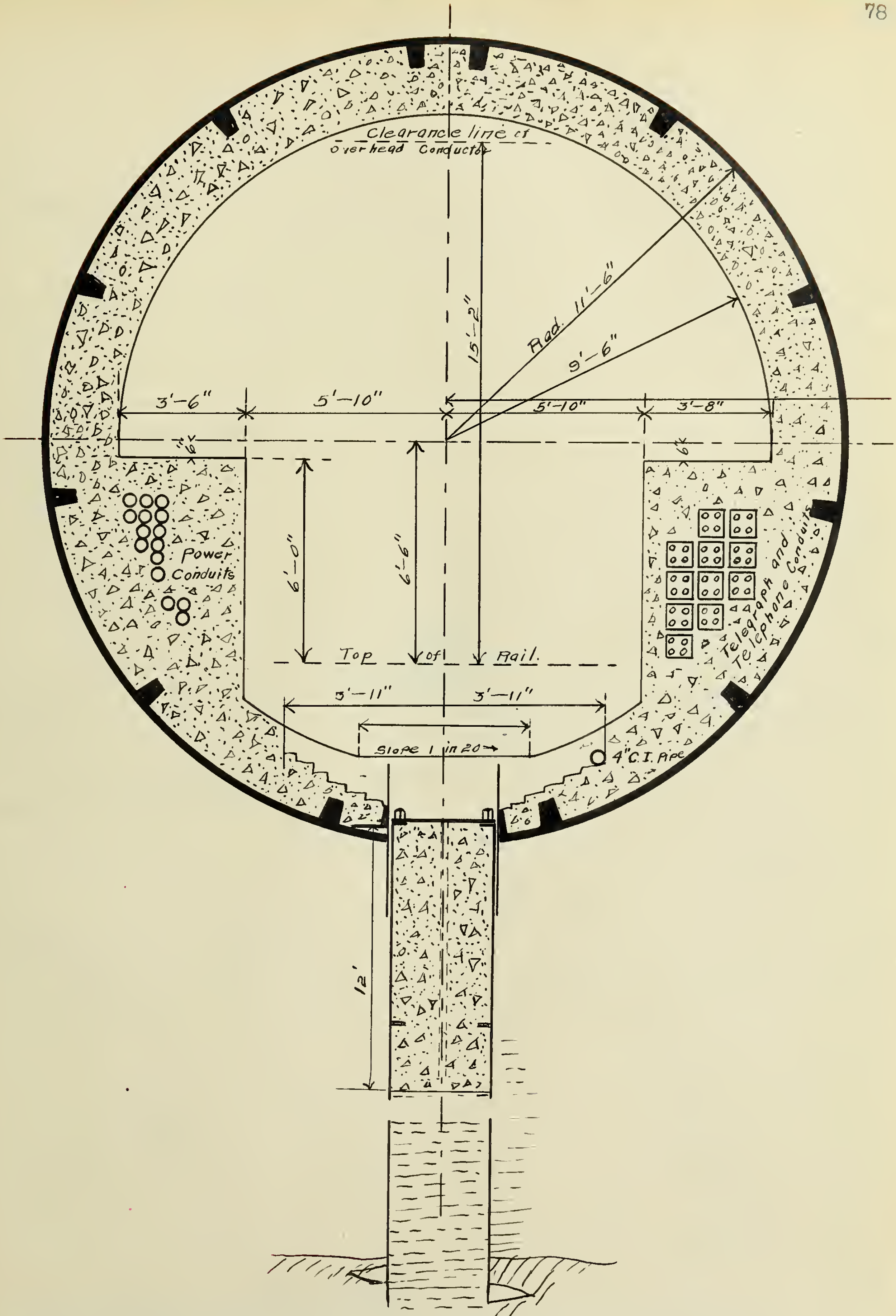

Jersey City
Manhattan
Brooklyn
Long Island City
1
2
3
4
5
6
7
8
9
10
11

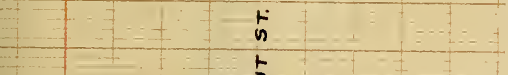
MAP SHOWING TUNNELS AT NEW YORK CITY

1 Penna. tunnel 33d St. to Wehawken.
2 Mc Adoo tunnel.
3 Ny and N.J. R.R. tunnel.
4 Battery Rapid Transit tunnel.
5 Old Slip to Brooklyn.
6 Maiden Lane tunnel.
7 Beekam St. tunnel
8 E 14th St. tunnel
9 Penna. tunnel 33d St. to L.I.Cy.
10 Belmont tunnel
11 Harlem River tunnel


Clearance line of
overhead Conductor
Rad. 11'–6"
9'–6"
15'–2"
3'–6"
5'–10"
5'–10"
3'–8"
6"
6"
6'–0"
6'–6"
Power
Conduits
Telegraph and
Telephone Conduits
Top of Rail.
3'–11"
3'–11"
Slope 1 in 20→
4" C.I. Pipe
12'

PENNA. R.R. NORTH RIVER TUNNEL

ROAD COMPANY

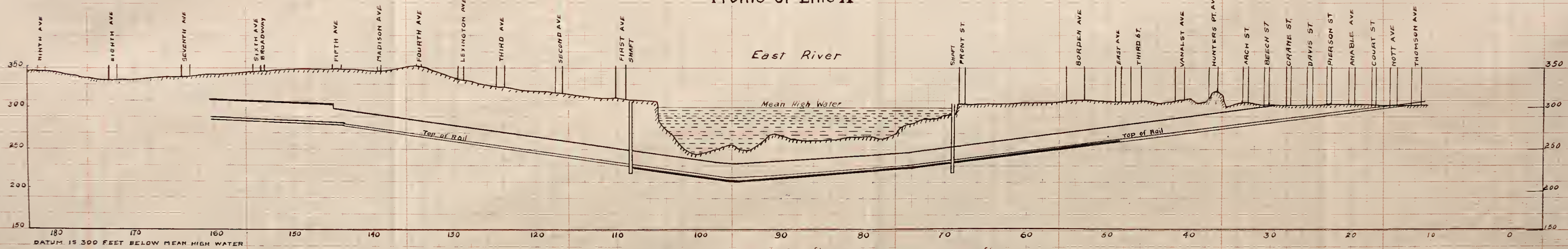

SHAFT
FRONT ST.
70
60

l Scale $1^{\text{in}} = 80^{\text{ft.}}$

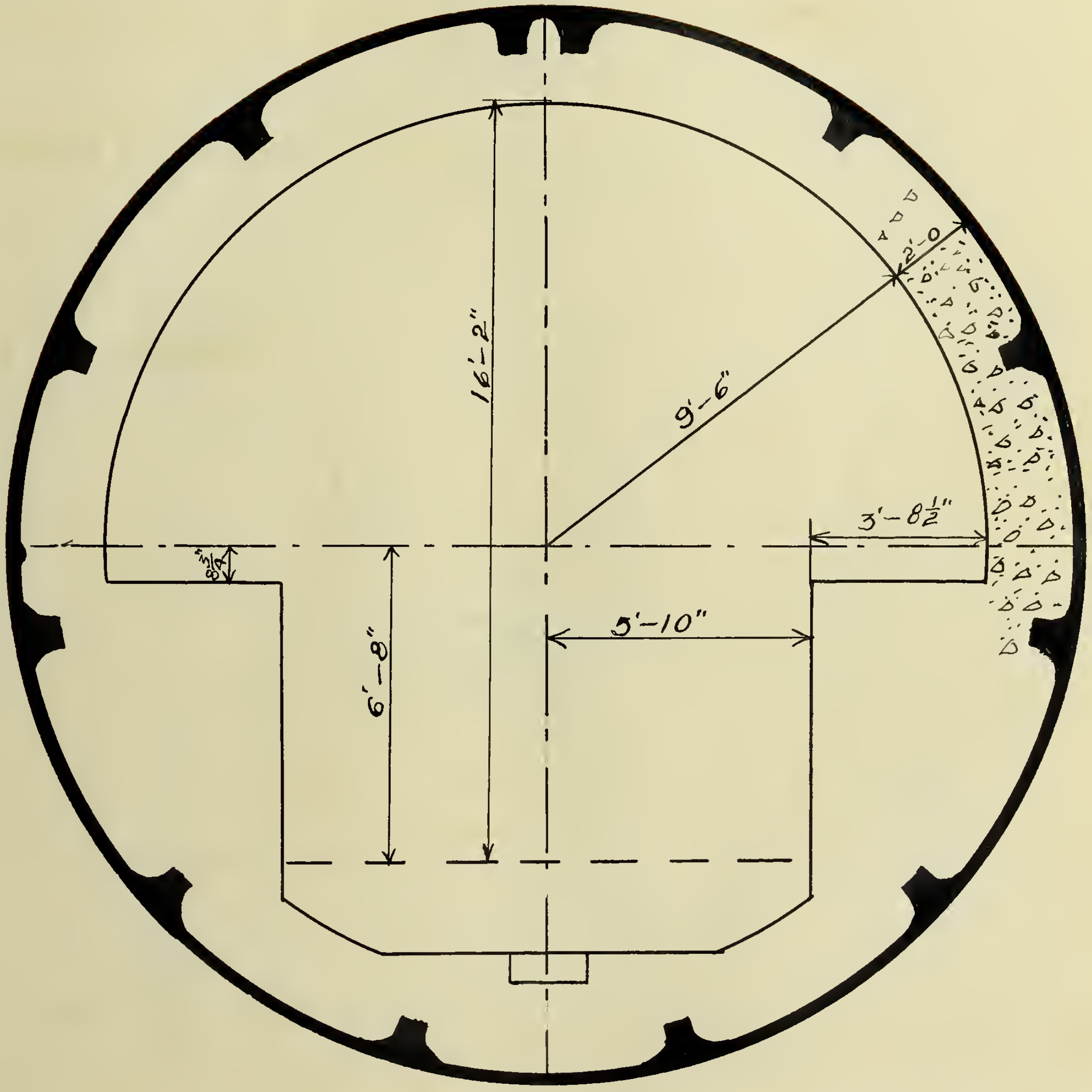
PENNSYLVANIA NEW YORK & LONG ISLAND RAILROAD COMPANY

EAST RIVER TUNNEL

Profile of Line A

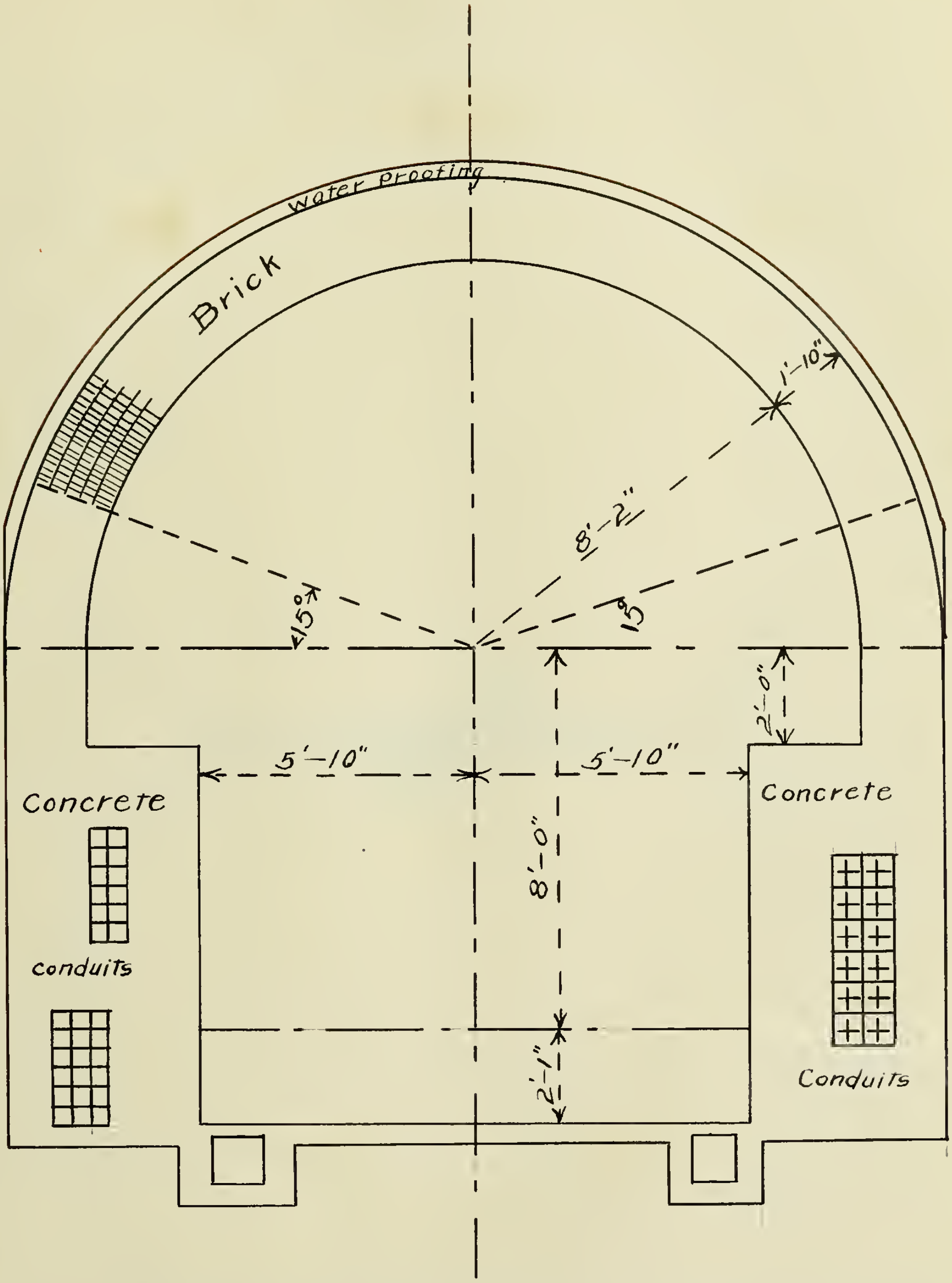

NINTH AVE
EIGHTH AVE
SEVENTH AVE
SIXTH AVE
BROADWAY
FIFTH AVE
MADISON AVE
FOURTH AVE
LEXINGTON AVE
THIRD AVE
SECOND AVE
FIRST AVE
SHAFT
East River
Mean High Water
SHAFT
FRONT ST.
BORDEN AVE
EAST AVE
THIRD ST.
VANALST AVE
HUNTERS PT. AVE
ARCH ST
BEECH ST
CRANE ST.
DAVIS ST
PIERSON ST
ANABLE AVE
COURT ST
NOTT AVE
THOMSON AVE
Top of Rail
Top of Rail
350
300
250
200
150
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
DATUM IS 300 FEET BELOW MEAN HIGH WATER

Horizontal Scale 1in=800ft. Vertical Scale 1in=80ft.


16'-2"
9'-6"
2'-0
3'-8½"
8¾"
5'-10"
6'-8"

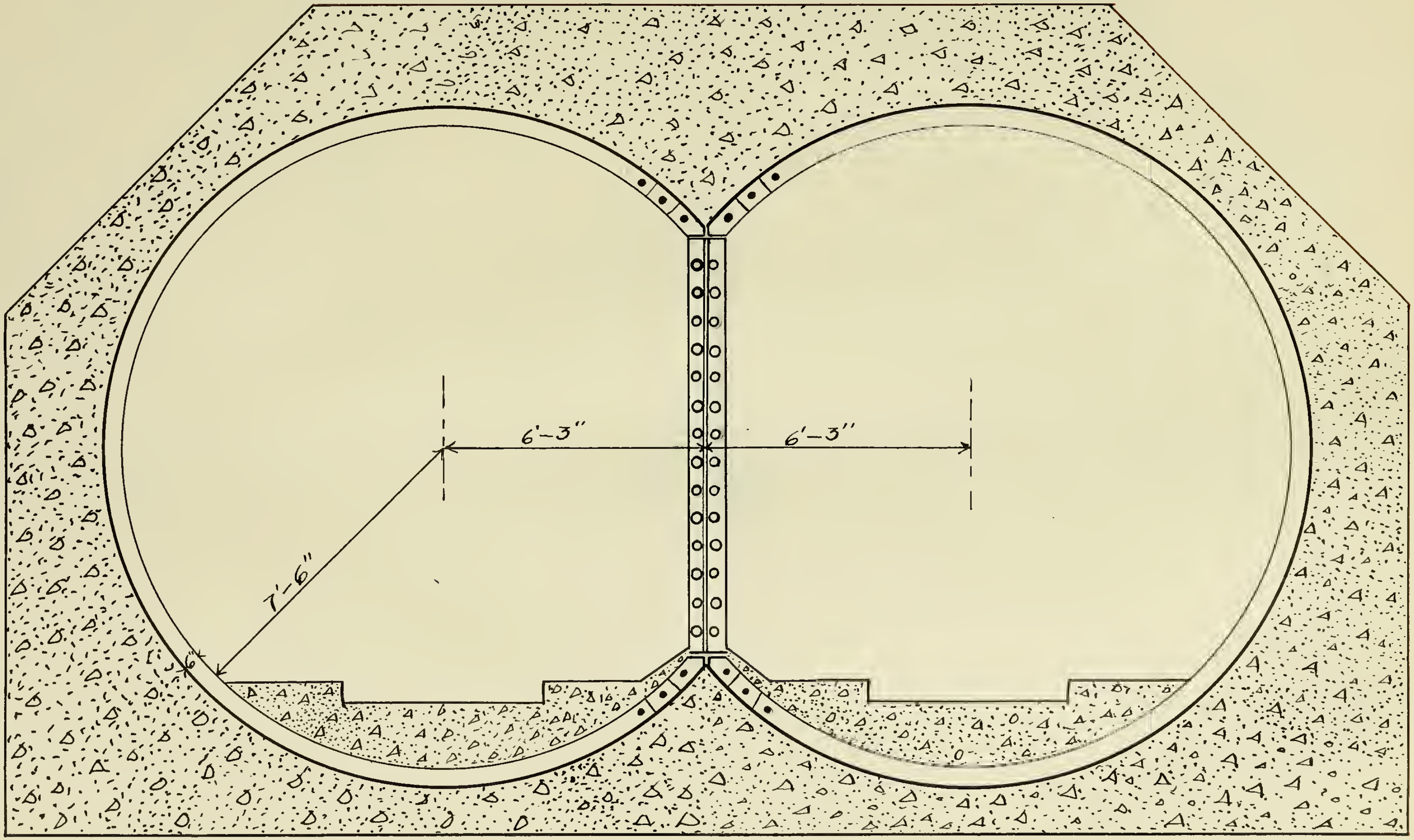
PENNA. R.R. EAST RIVER TUNNEL
Sub-aqueous Section

[illegible]
[illegible]

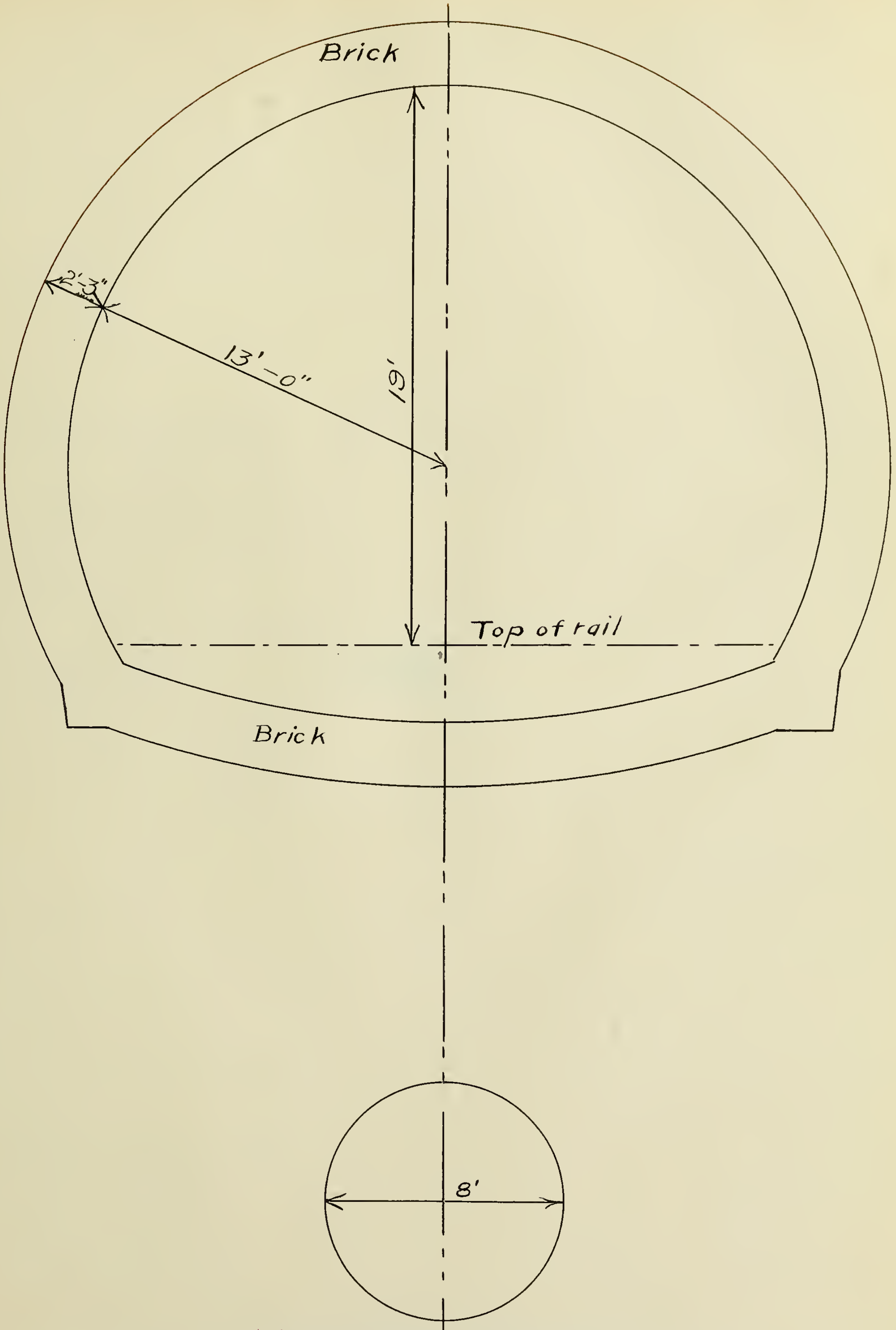

water proofing
Brick
1'-10"
8'-2"
15°
13°
2'-0"
5'-10"
5'-10"
Concrete
Concrete
8'-0"
conduits
Conduits
2'-1"

PENNA. R.R. EAST RIVER TUNNEL

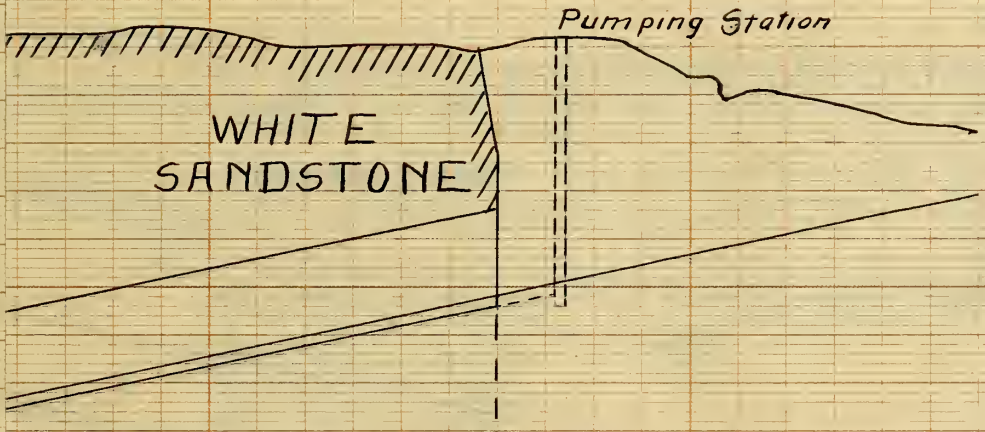
Land Section



HARLEM RIVER TUNNEL

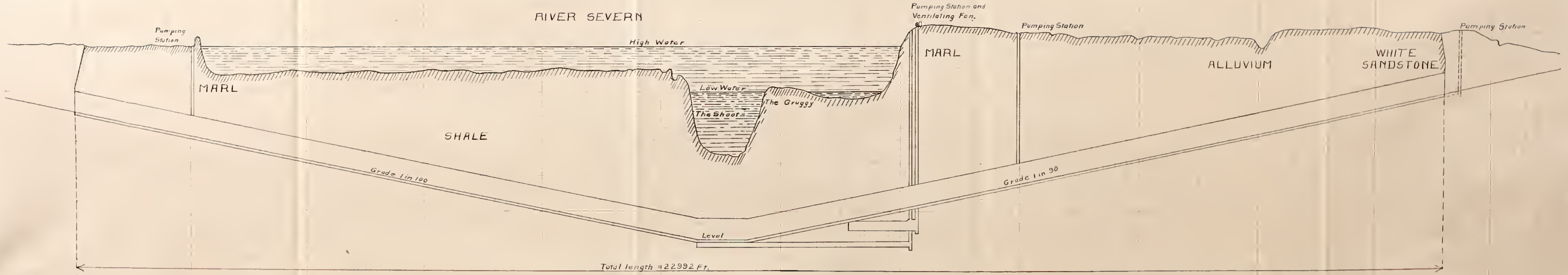

Brick
2'-3"
13'-0"
19'
Top of rail
Brick
8'

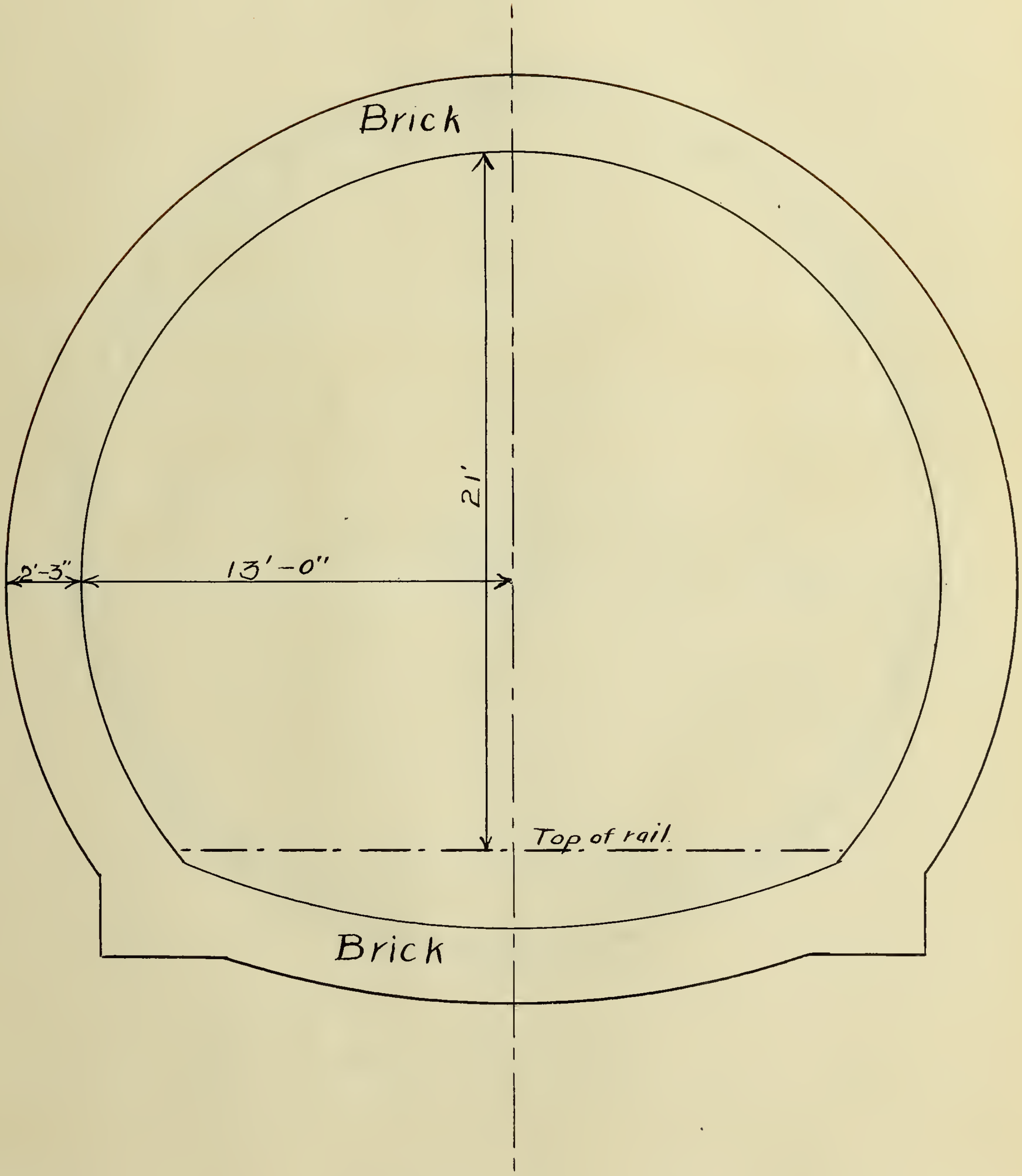
MERSEY TUNNEL


Pumping Station
WHITE SANDSTONE

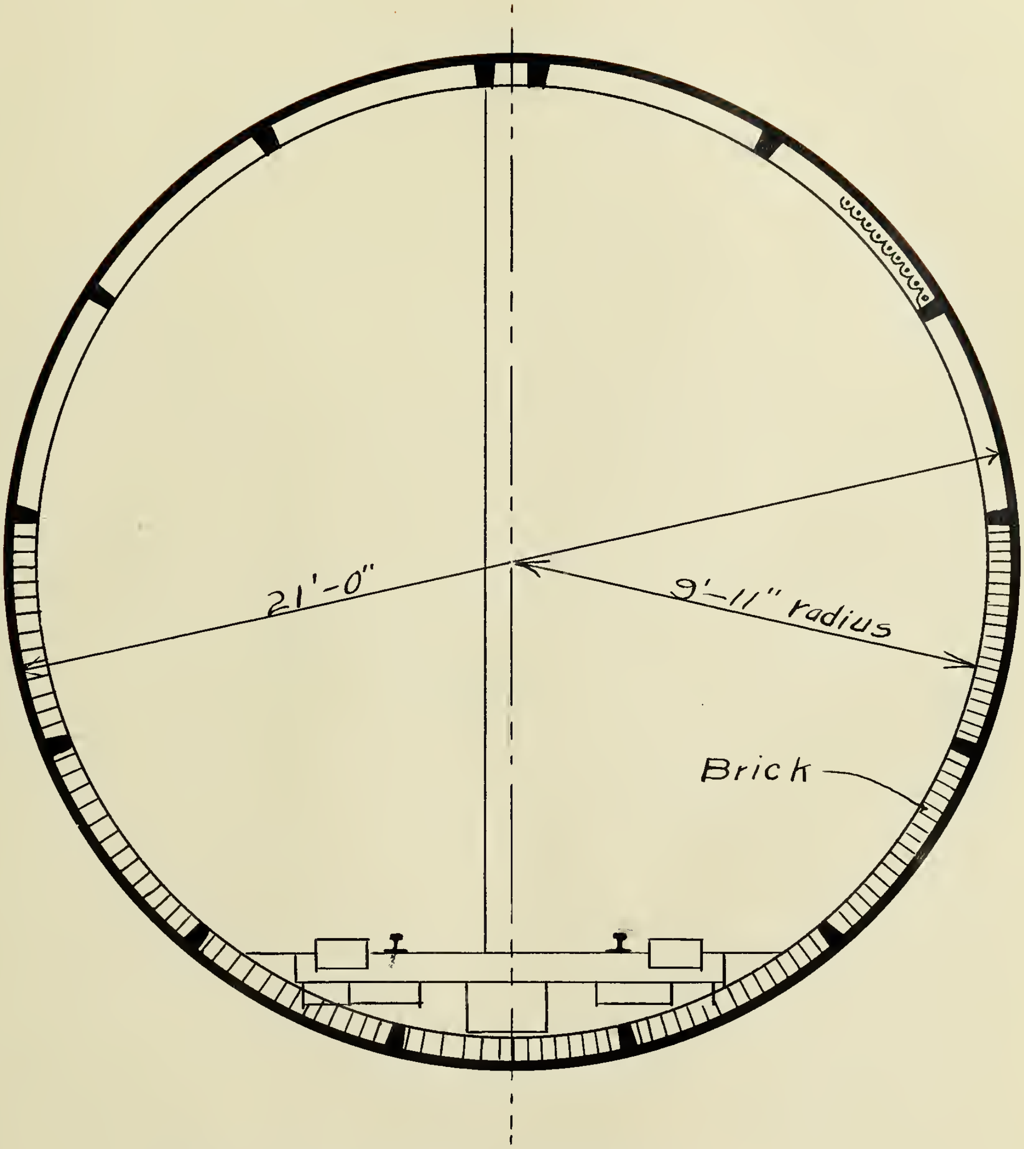
PROFILE OF THE SEVERN RAILWAY TUNNEL

Scales Hor. 1" = 800'
Vert 1" = 40'

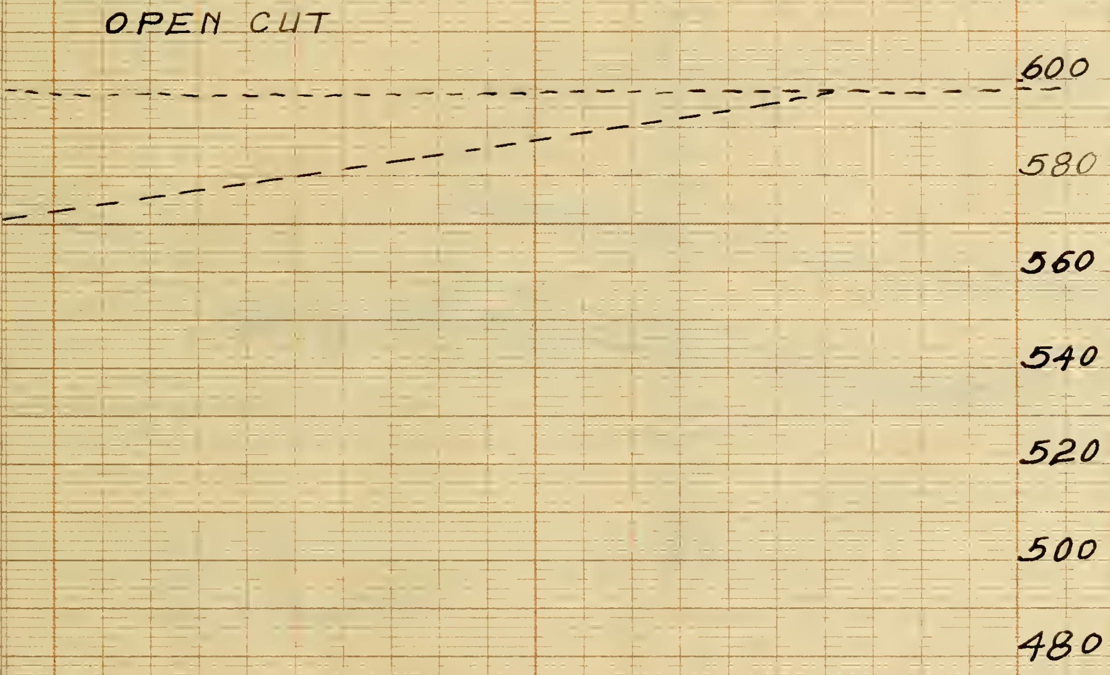

RIVER SEVERN
Pumping Station
High Water
MARL
Low Water
The Gruggy
The Shoots
SHALE
Grade 1 in 100
Level
Pumping Station and Ventilating Fan.
MARL
Pumping Station
ALLUVIUM
WHITE SANDSTONE
Pumping Station
Grade 1 in 90
Total length = 22992 Ft.

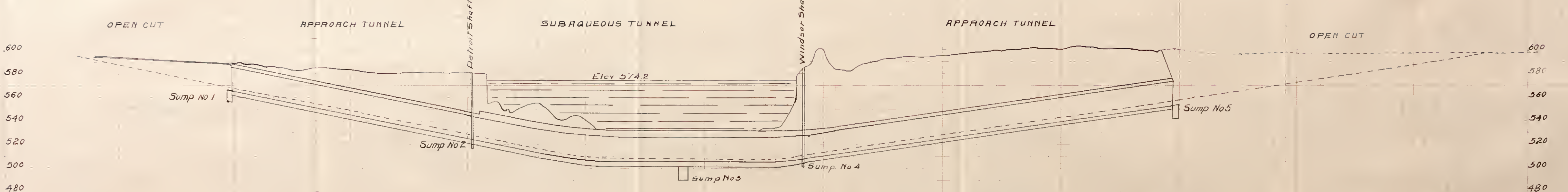

Brick
21'
2'-3"
13'-0"
Top of rail
Brick

SEVERN TUNNEL


21'-0"
9'-11" radius
Brick

ST. CLAIR TUNNEL


OPEN CUT


OPEN CUT
APPROACH TUNNEL
Detroit Shaft
SUBAQUEOUS TUNNEL
Windsor Shaft
APPROACH TUNNEL
OPEN CUT
600
580
560
540
520
500
480
Elev 574.2
Sump No 1
Sump No 2
Sump No 3
Sump No 4
Sump No 5
600
580
560
540
520
500
480

PROFILE OF DETROIT RIVER TUNNEL

SCALE: HOR 1"=400'
VER 1"=40'

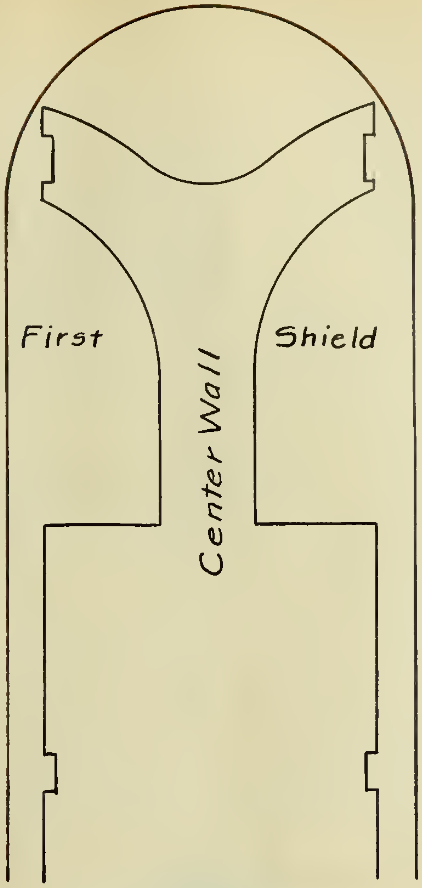

First
Shield
Center Wall

Fig. 1

Diagrams showing method of construction of the Michigan Central tunnel at Detroit, Michigan.

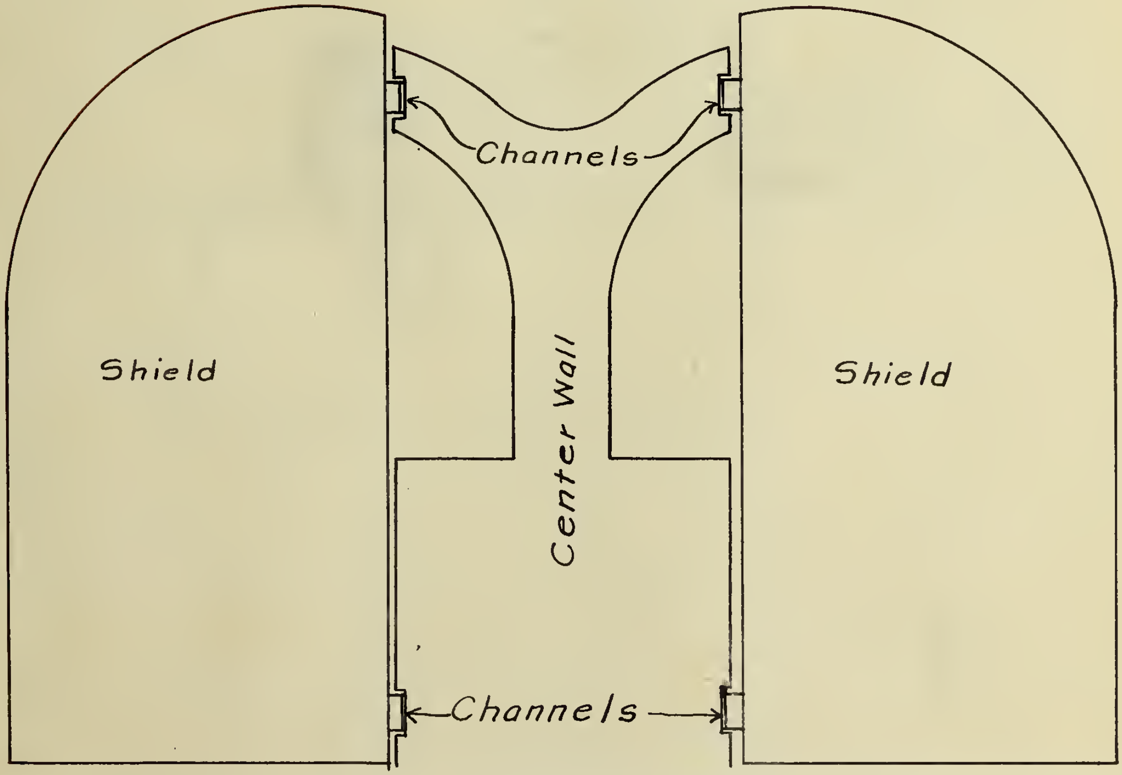
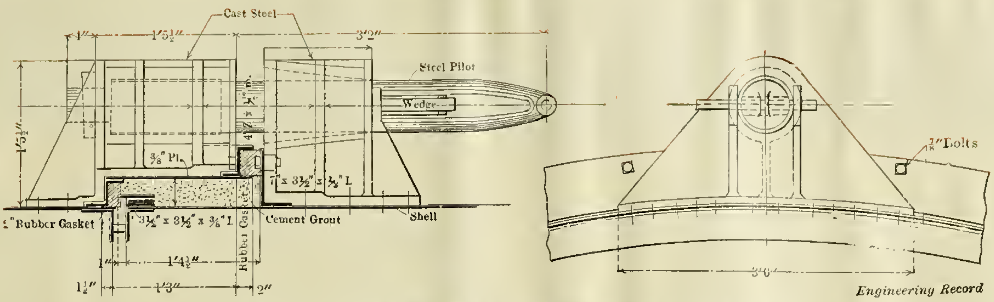
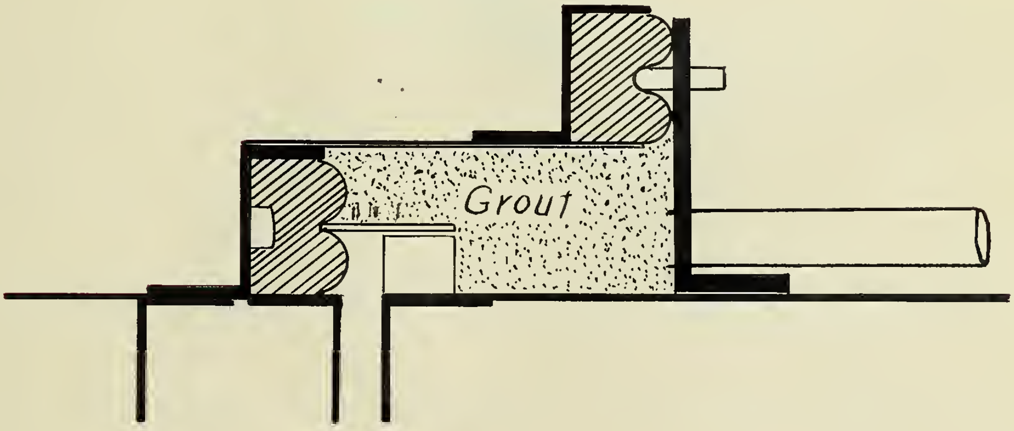

Channels
Shield
Center Wall
Shield
Channels

Fig. 2.

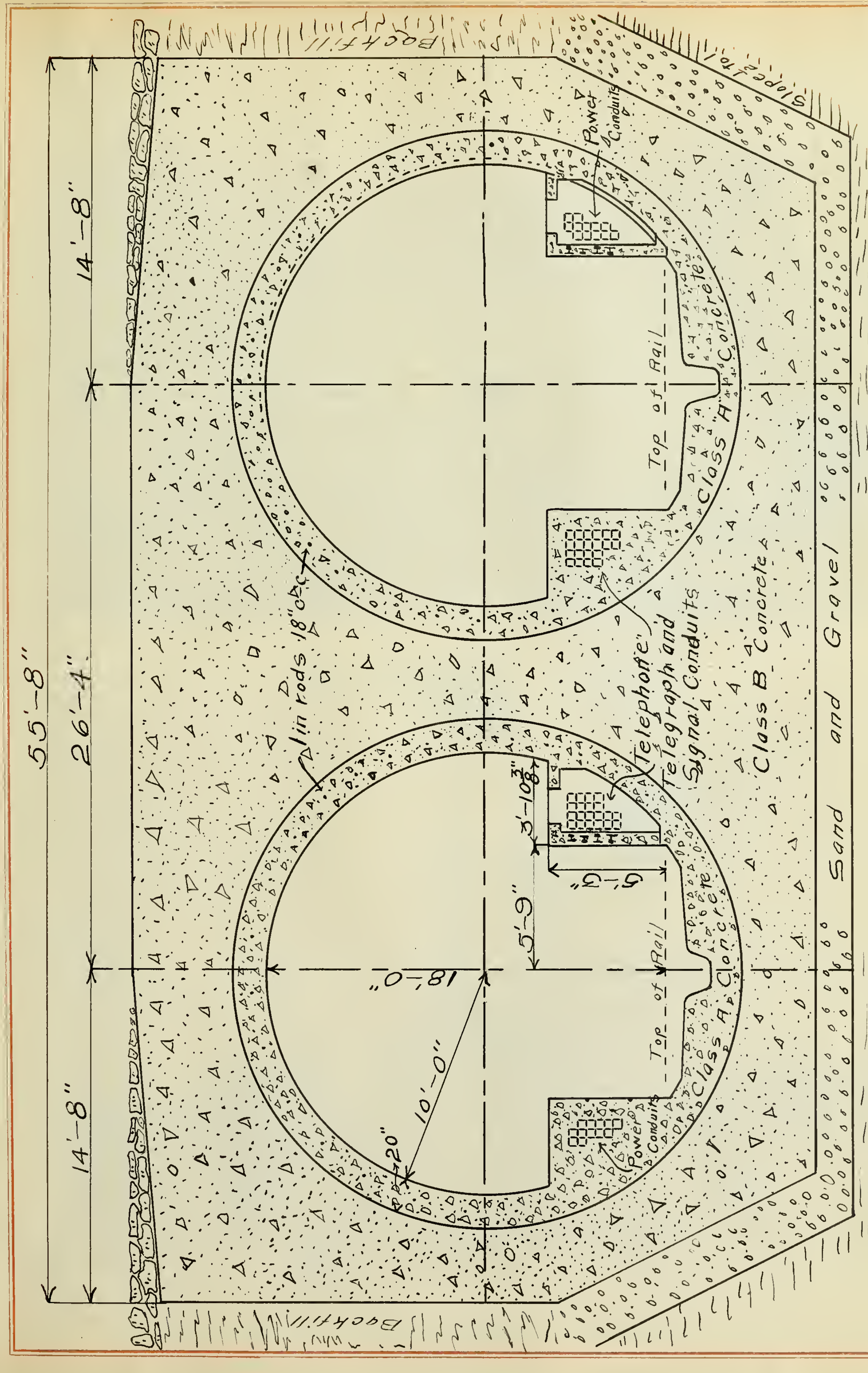

Cast Steel
1"
1'5½"
3'2"
Steel Pilot
Wedge
1'5½"
⅜" Pl.
7"x 3½" x ½" L
½" Rubber Gasket
3½" x 3½" x ⅜" L
Cement Grout
Shell
Rubber Gasket
1"
1'4½"
1½"
1'3"
2"
⅞" Bolts
3'6"

Engineering Record

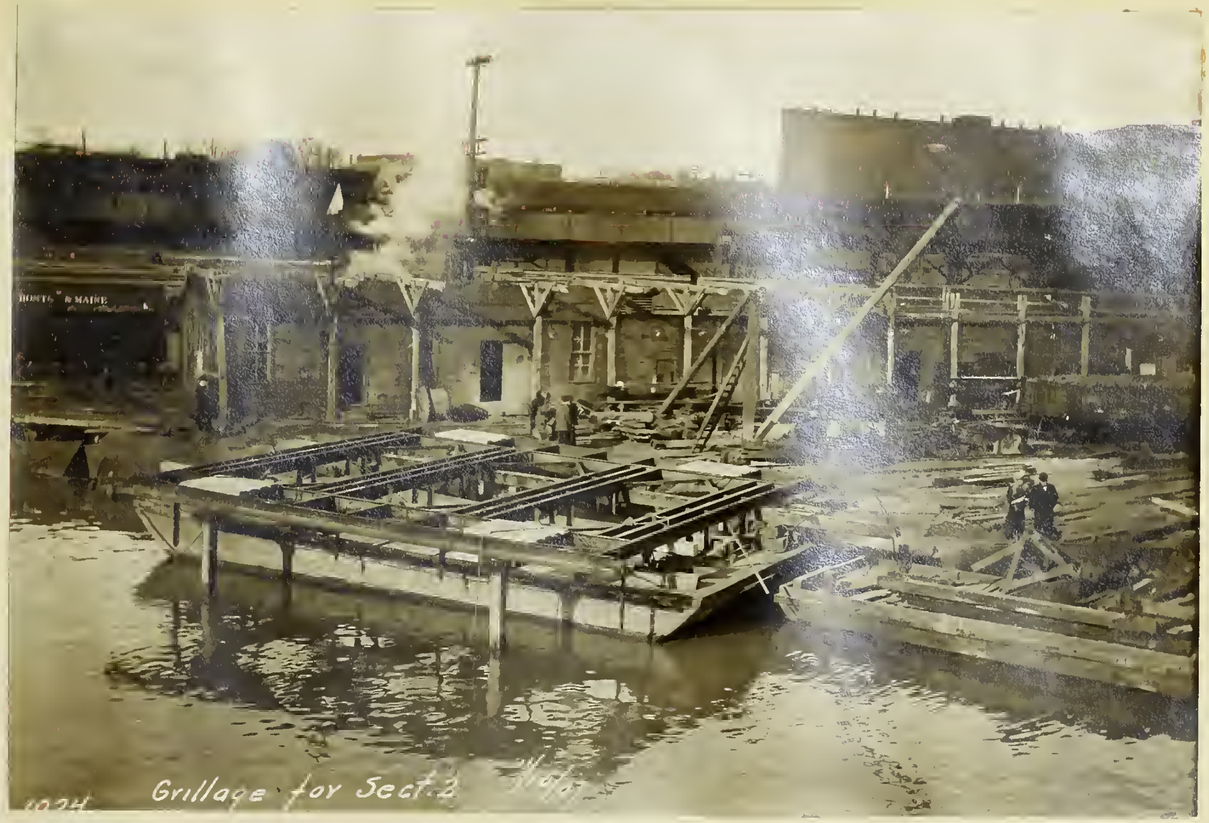
Detail of Tube Splices, Detroit River Tunnel.



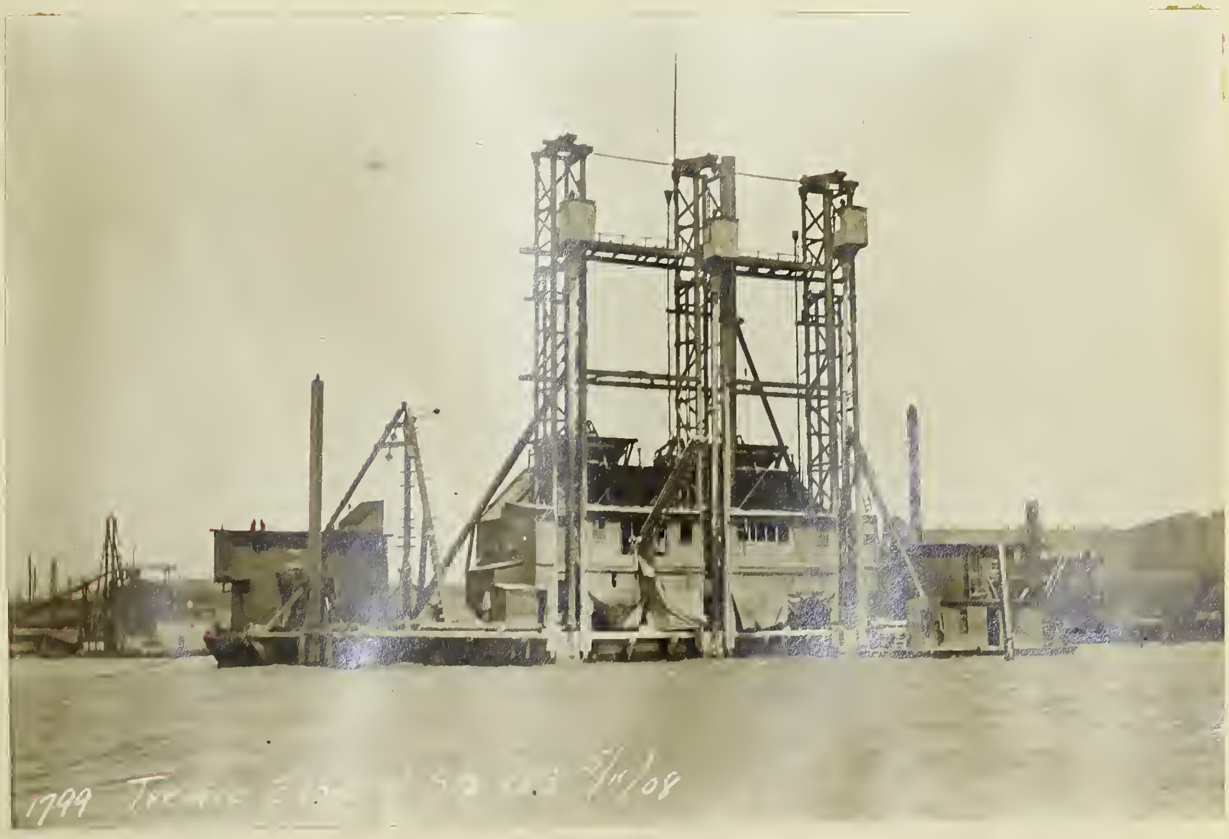
SECTION OF TUBE SPLICE


55'-8"
26'-4"
14'-8"
14'-8"
Backfill
Backfill
Slope 1 to 1
Power Conduits
Power Conduits
Top of Rail
Top of Rail
Class "A" Concrete
Class "A" Concrete
Telephone Telegraph and Signal Conduits
Class B Concrete
Sand and Gravel
1 in rods 18" c-c
3'-10⅜"
5'-9"
5'-5"
18'-0"
10'-0"
20"

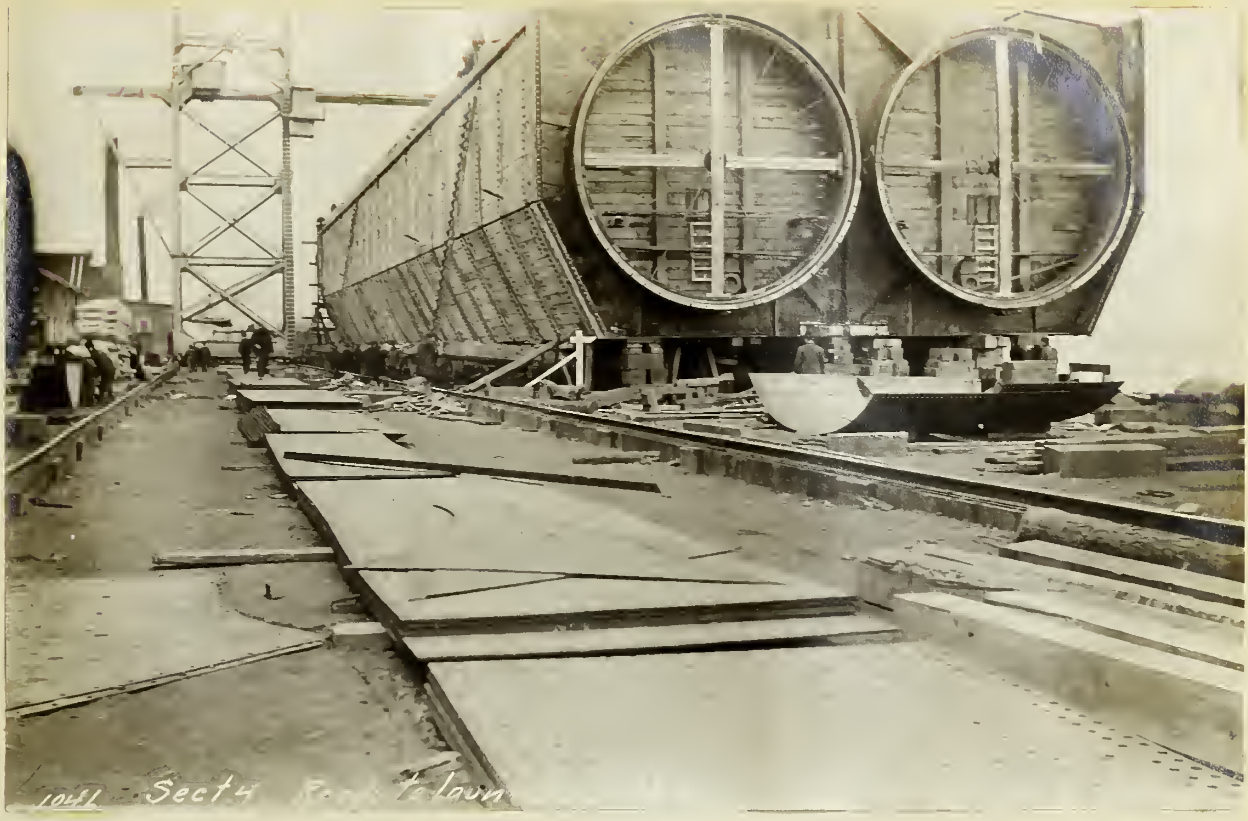
DETROIT RIVER TUNNEL

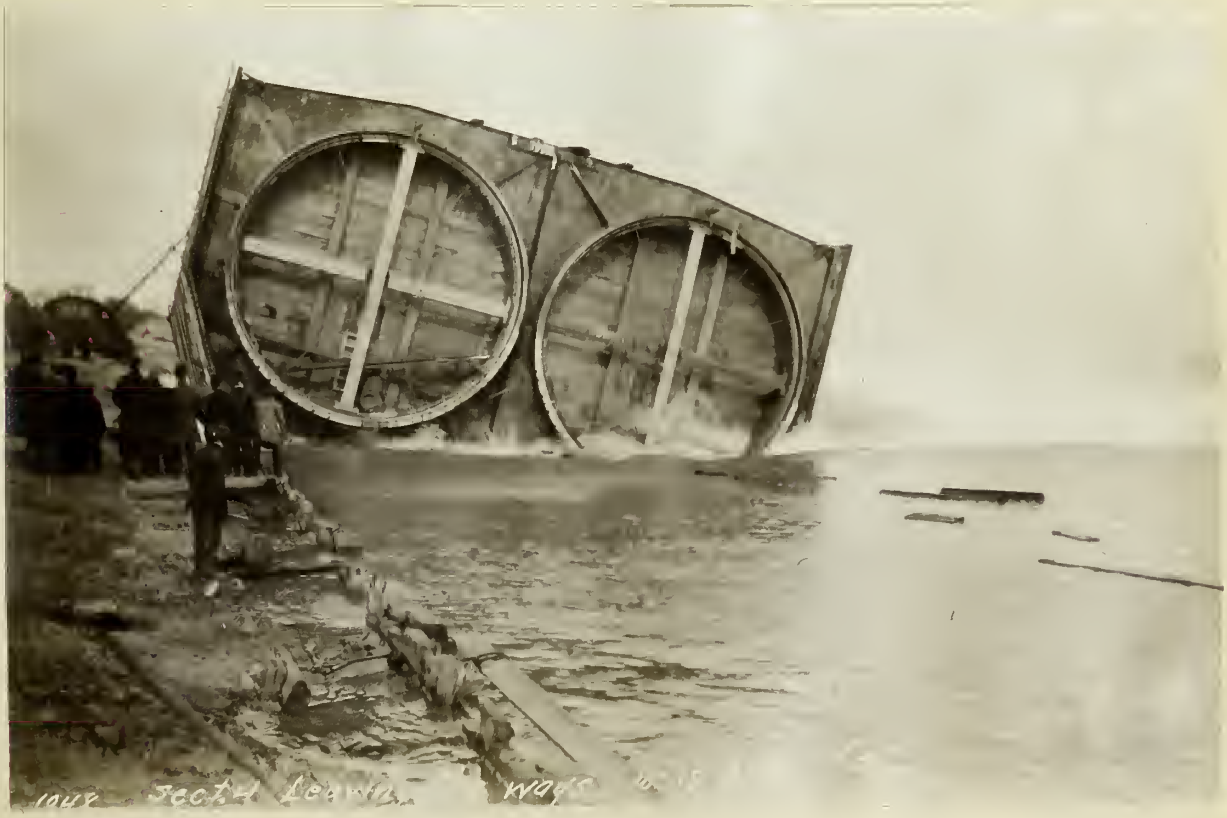


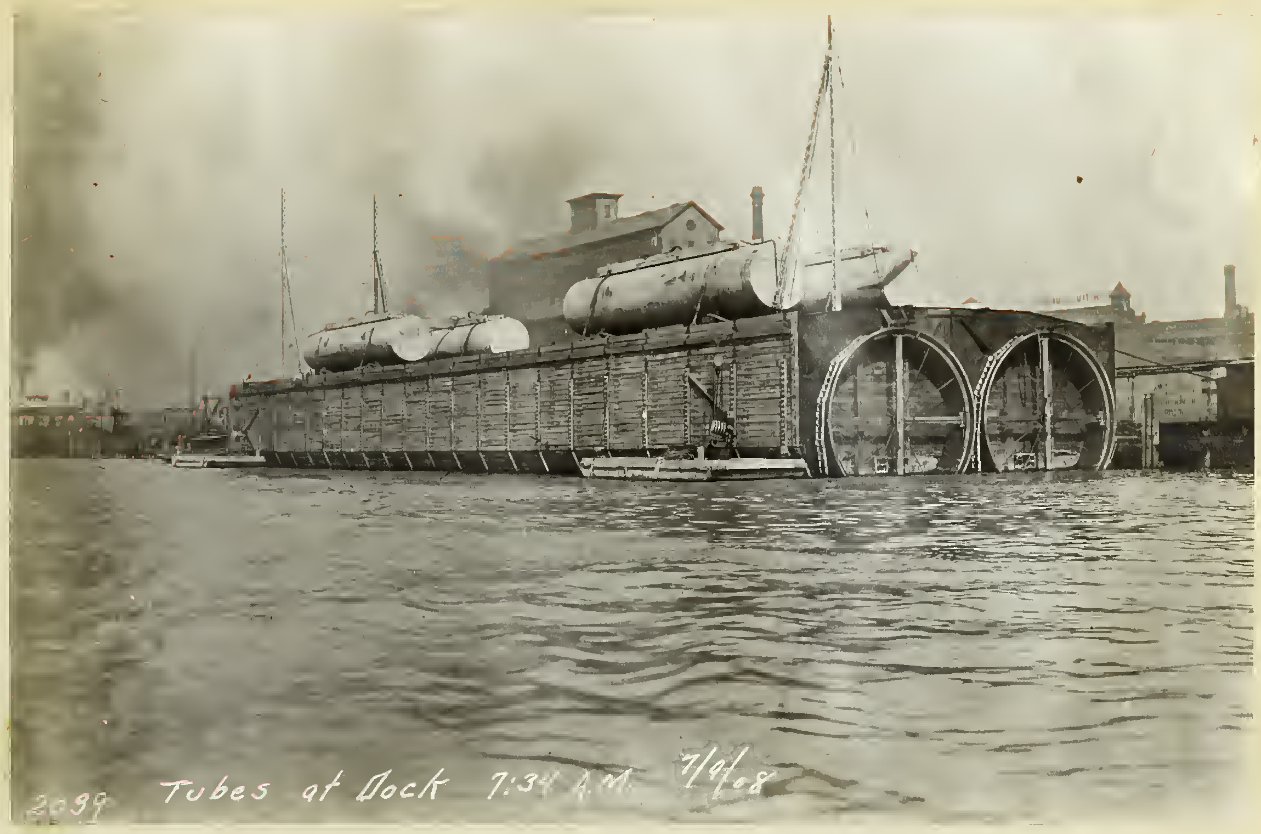
1924 Grillage for Sect. 2 [illegible]



1799 Tremie [illegible] 7/11/08

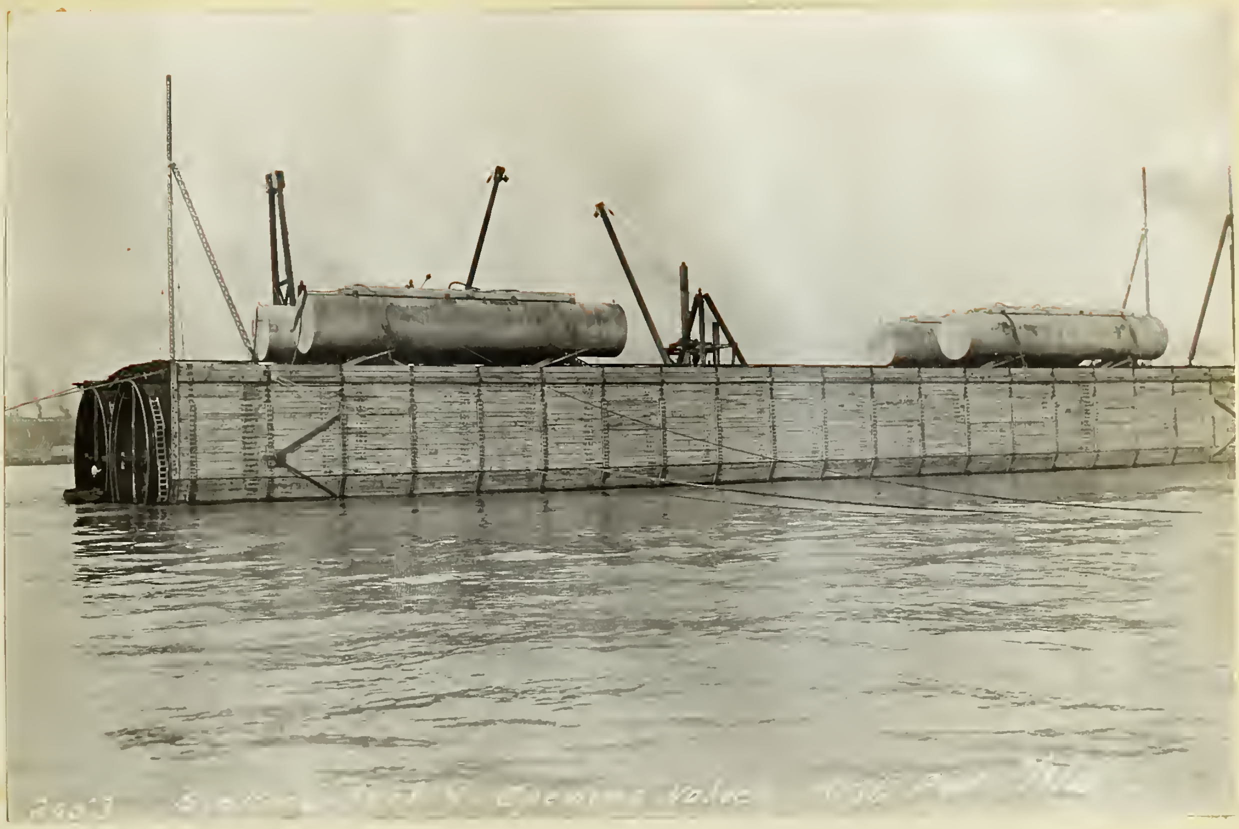

1046 Sect 4 R [illegible] to laun

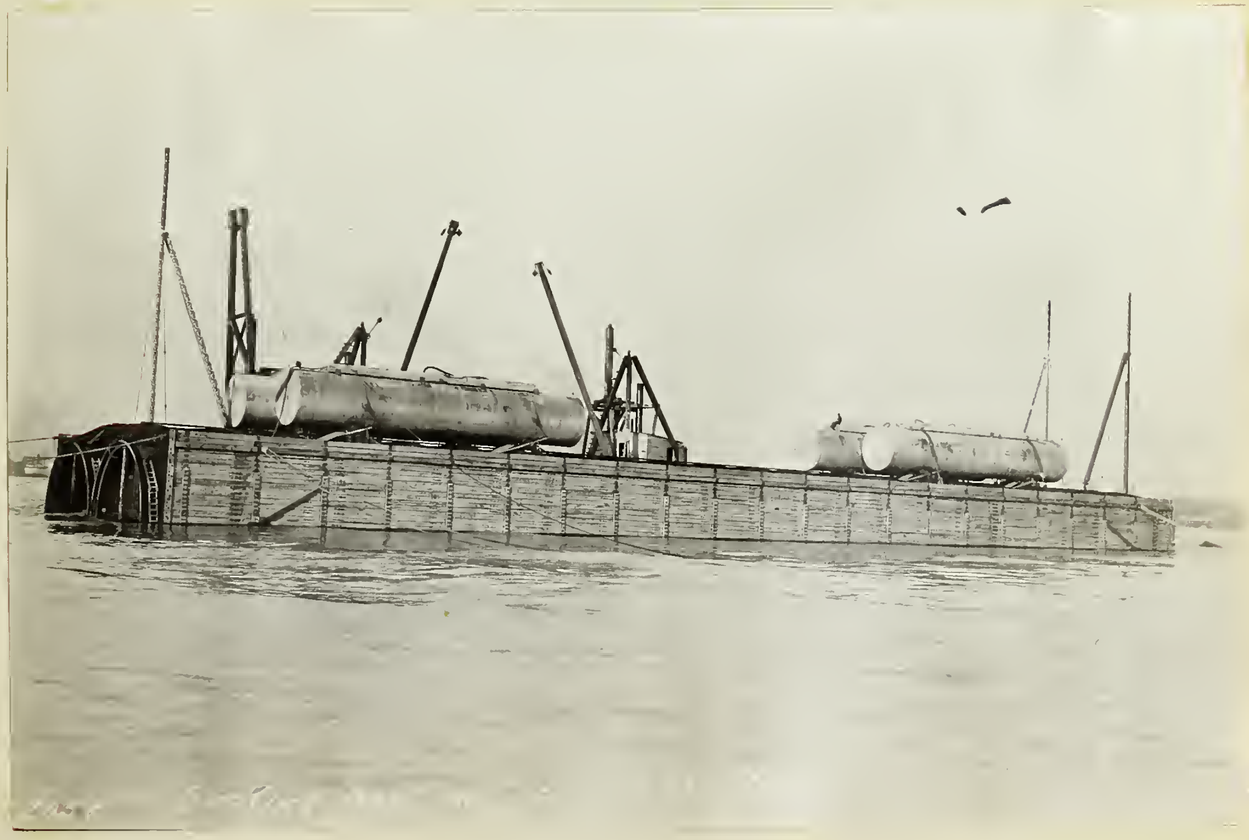

1048 Sect 4 Leavin [illegible] ways

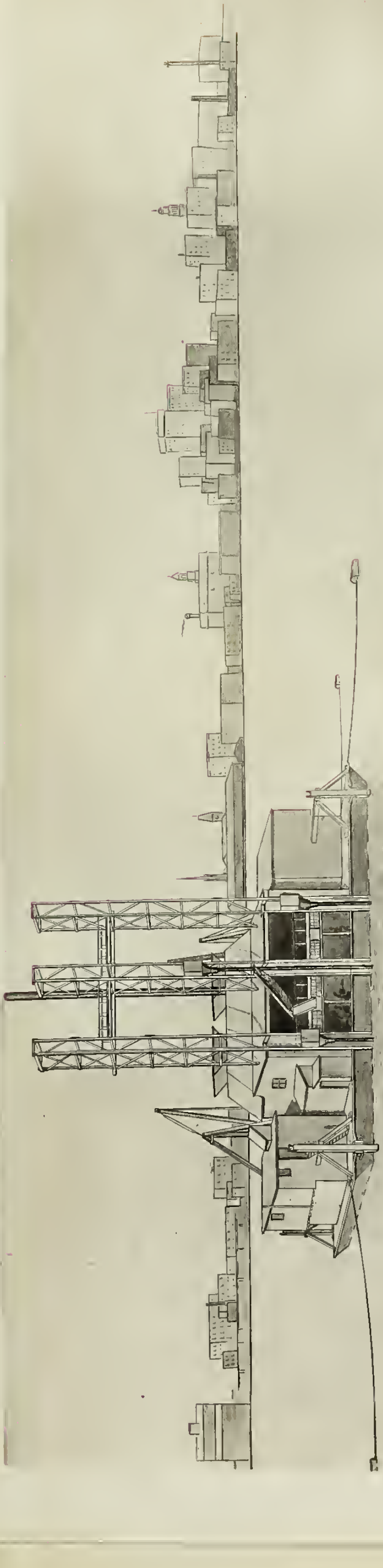


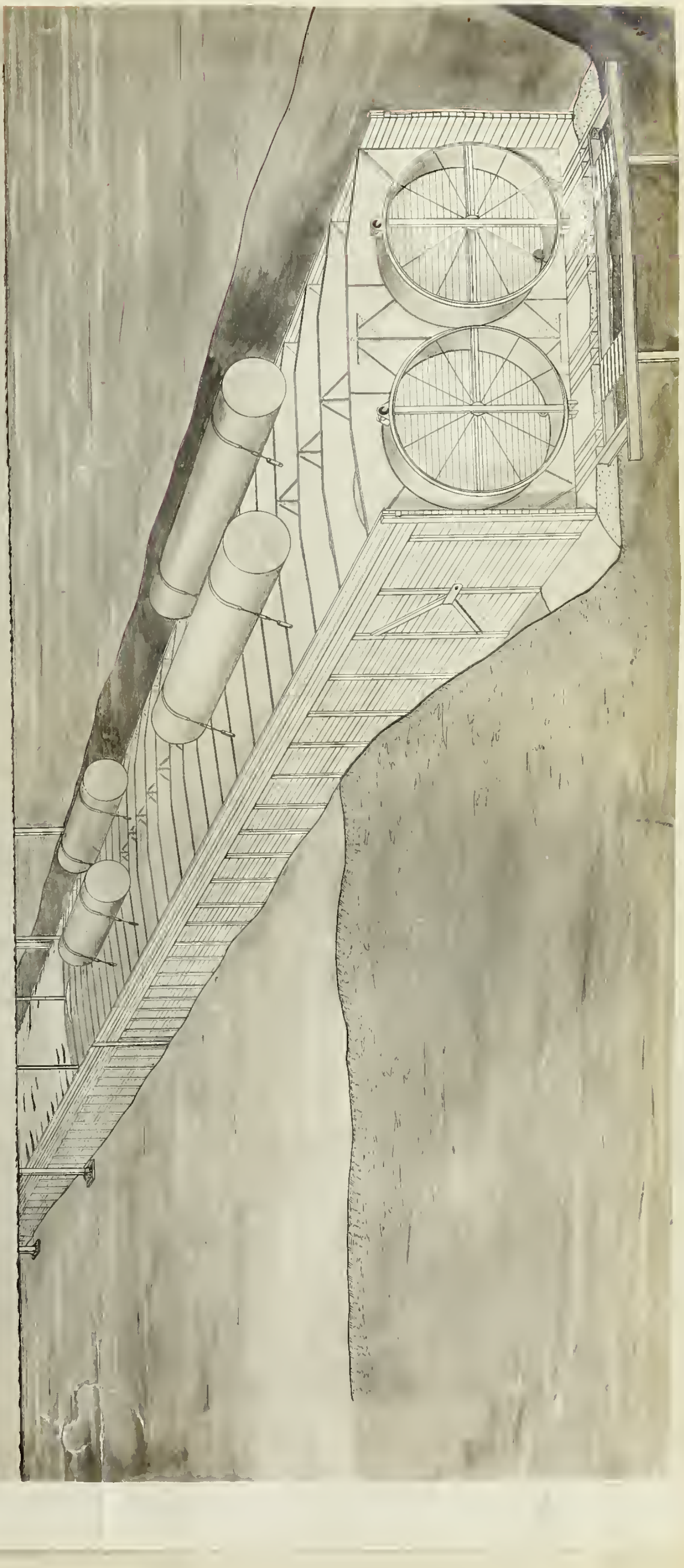
2099 Tubes at Dock 7:34 A.M. 7/9/08

[illegible]


8603 Sinking Test 5 Opening Valve 1:30 P.M.


Sinking





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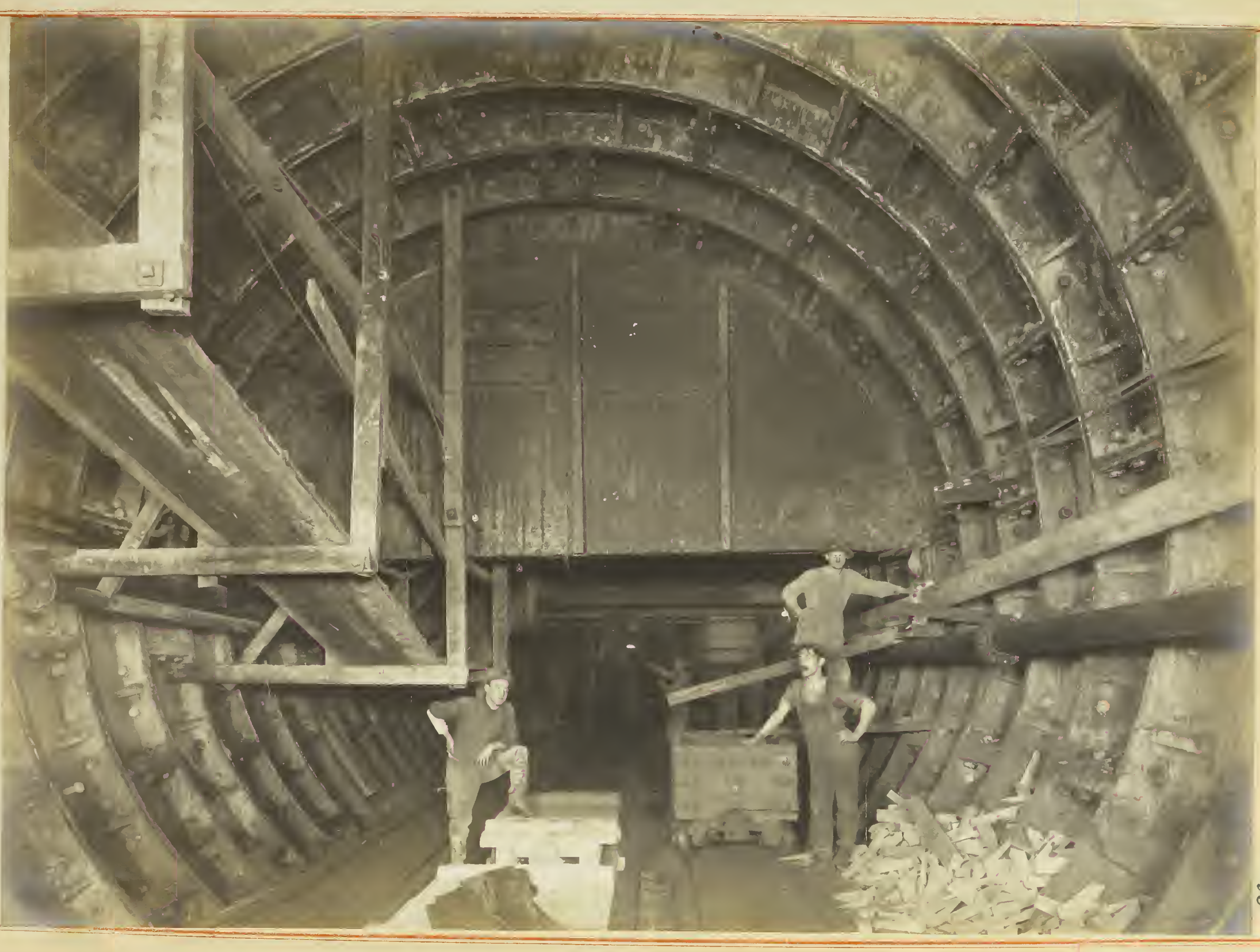
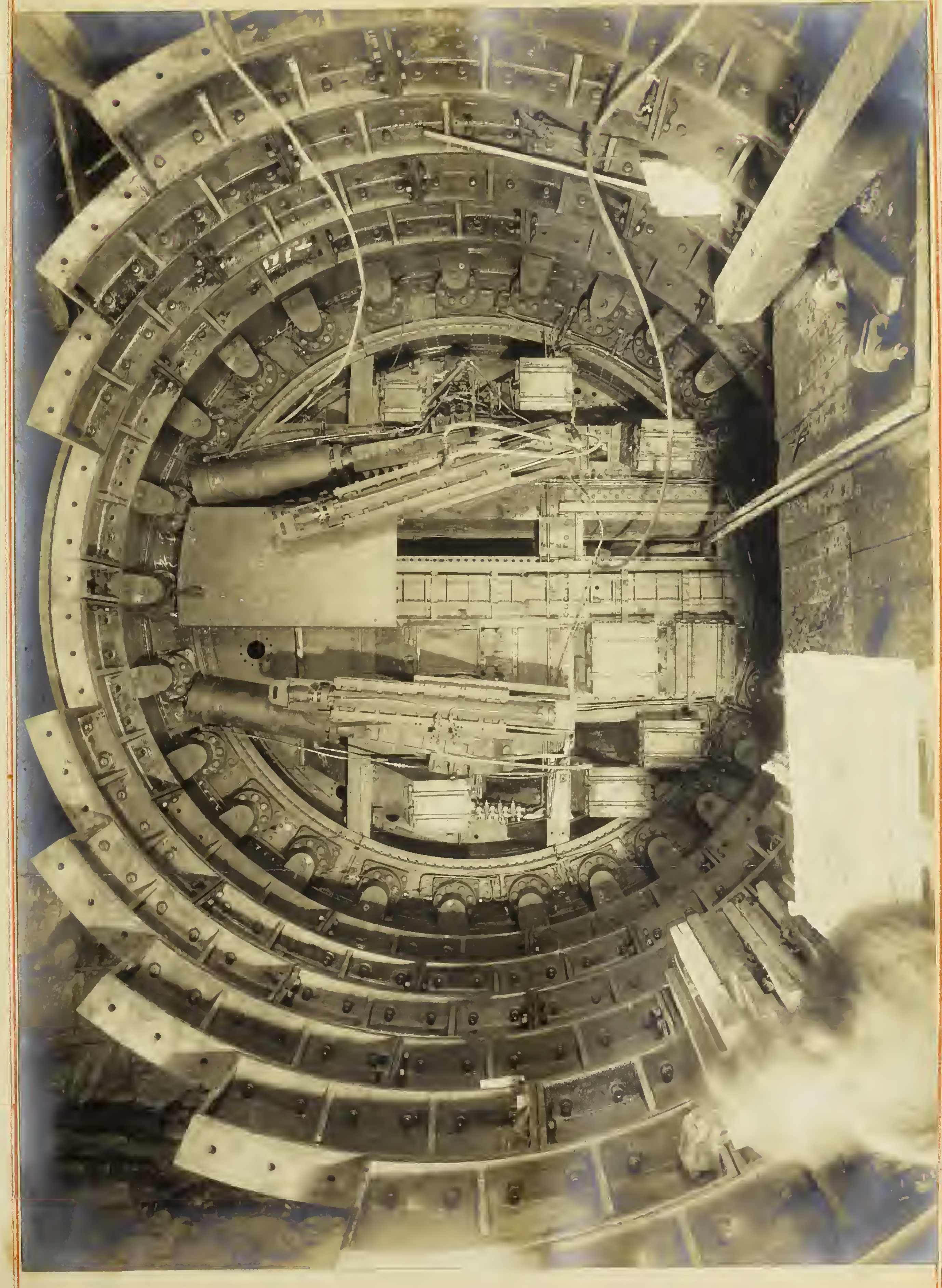
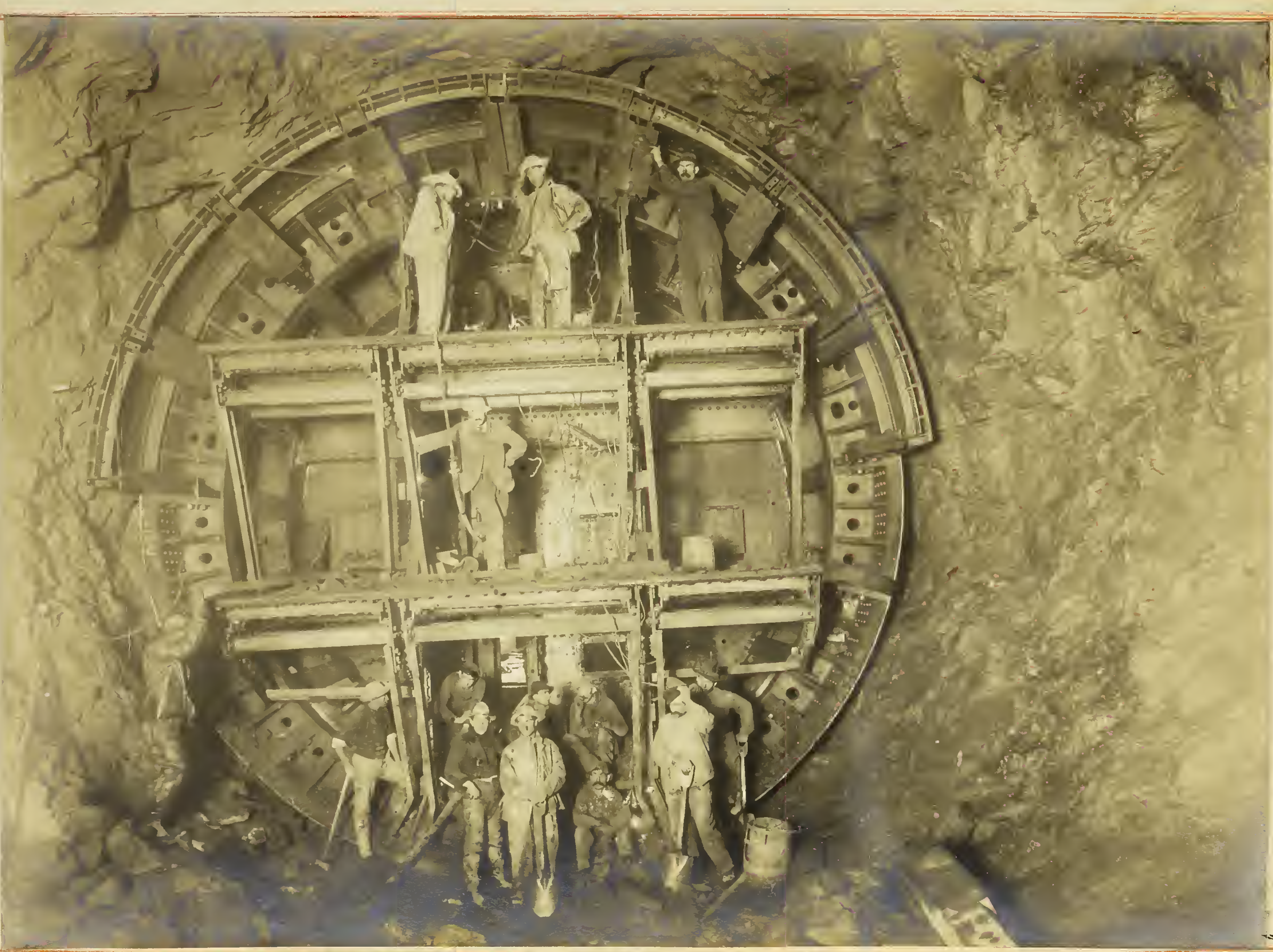


[illegible]
[illegible]





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